United States Air Force Scientific Advisory Board

Report on

Technology Options for Improved Air Vehicle Fuel Efficiency

Executive Summary and Annotated Brief

SAB-TR-06-04
May 2006

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Scientific Advisory Board

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Foreword

As crude oil prices and worldwide competition for fuel continue to increase, there are increasing pressures on the United States to simultaneously conserve fuel as well as seek new sources of energy for power generation and transportation systems. Within the U.S. military, increasing costs of fuel directly affect the ability to carry out military missions. Hence it is imperative that the Department of Defense, and the Air Force in particular (as the largest consumer of fuel within the DoD), explore ways in which improved fuel efficiency as well as alternative sources of fuel may be realized.

The Air Force Scientific Advisory Board was thus tasked by the Air Force leadership to perform a “quick look” study exploring potential scientific and technological solutions that could impact energy and fuel efficiency. The study was conducted between November 2005 and January 2006, after which study briefings to the AF and DoD leadership were presented. The study’s briefing charts (absent facing page text) were publicly released in early March 2006. The present report, consisting of an executive summary and annotated briefing with an elaboration of additional promising technologies (Appendix E), is intended to provide a complete discussion on the background, issues, findings, and recommendations from the study, which focused primarily on air vehicles.

It is hoped that this document will serve as one of many within the U.S. government that will help to spur our nation toward a more secure and robust energy future.

Ann R. Karagozian

Professor Ann R. Karagozian
SAB Fuel Efficiency Study Chair
May 2006

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Executive Summary

Introduction

The US Air Force Scientific Advisory Board conducted a "quick look" study on the subject of **Technology Options for Improved Air Vehicle Fuel Efficiency** during the November 2005 – January 2006 time frame.

The SAB was tasked in the Fall of 2005 by the USAF leadership to explore potential scientific and technological solutions that could impact energy and fuel efficiency within the Air Force. In scoping the problem, the SAB Fuel Efficiency Study members considered the following. At present, the United States imports roughly 63% of its crude oil from foreign sources, and its rate of consumption of fossil fuels is increasing by approximately 1.5% per year, while its production capability has slightly decreased in the last decade. Increasing oil demand by highly populous nations such as India and China, at rates nearly four times that of the United States, will increase (and are increasing) the potential for geopolitical tension regarding fossil fuels**.** Hence fuel availability, as well as more efficient utilization of fuel, will be increasingly critical issues for the foreseeable future. While the Department of Defense consumes only a small fraction of fuel from crude oil utilized nationwide (less than 2%), the Air Force consumes nearly 60% of all fuels utilized by the DOD, and within the Air Force over 80% of the fuel consumed is comprised of aviation fuels. Hence within the limitations of a quick examination of the scientific and technical issues surrounding energy efficiency within the Air Force, this SAB study focused on fuel consumption, utilization, and improved fuel efficiency associated with **air vehicles**. In fact, because the majority of aviation fuel within the Air Force is consumed by the mobility fleet (tankers and transport aircraft), the study emphasized an examination of fuel efficiency associated with large mobility aircraft, as opposed to fighter or bomber aircraft.

Air vehicle fuel efficiency can be impacted from a technological perspective by improved engine efficiency (e.g., though a reduction in the thrust specific fuel consumption, TSFC, or by an increase in the engine's overall efficiency, η_o), by improved vehicle aerodynamic characteristics (e.g., through an increase in the lift-to-drag or L/D ratio), and/or by reduction in the aircraft's structural weight (operating empty weight or OEW). Hence the fuel efficiency study focused on potential technology solutions that could impact these three areas, in addition to exploring a limited number of operational solutions. Alternative fuels were also examined in the study, not as a means of necessarily improving an aircraft's fuel efficiency, but rather as a means of providing a more secure, assured source of fuel to be able to carry out Air Force missions.

Overall Findings and Recommendations

Findings and recommendations are categorized within the fuel efficiency study according to the impact of a given technological (or other) solution on the aircraft engine performance, aerodynamics, or aircraft structure, and on impact as an operational solution or an alternative fuel solution. Findings on solutions were also identified as having potential impact in the near term (within 0-5 years), mid term (5-15 years in the future), and far term (more than 15 years in the future). While the fuel efficiency study did not examine detailed development or life cycle costs for the potential solutions, there was a notional understanding of the magnitude of cost of

implementation, and hence the potential impact on fuel efficiency per cost (or notional "benefit-to-cost" ratio) was used as a metric for comparison. It should be noted that the "fully burdened cost of fuel," a term used to represent additional costs associated with transporting fuel overseas, was not explicitly considered in the study, but in fact should be utilized appropriately when assessing, for example, the costs and benefits associated with re-engining options.

Engine-Related Solutions. In the near term, even relatively simple solutions such as on-wing engine wash (performed routinely in the airline industry) could have immediate benefits for AF engine efficiency at a relatively low cost. In the mid term, re-engining at least part of the current fleet of mobility aircraft with contemporary high bypass ratio engines, and/or re-engining current aircraft with engines yet in the development stage are both seen as promising for improved fuel efficiency, yet with a relatively high cost of implementation. It is recommended that a more detailed study on re-engining of AF mobility aircraft be carried out. In the mid-to-far term, many of the active control and high temperature sensor technologies for fuel efficiency that are being pursued through the VAATE (Versatile Affordable Advanced Turbine Engine) program hold real promise for impacting efficient engine performance. Far term solutions that also have potential benefits, yet with relatively high costs, are revolutionary engine alternatives, including wave rotor topping cycles for the gas turbine cycle, and detonation-based engine cycles.

Aerodynamic Solutions. In the near term, wing retrofits such as winglets have demonstrated the potential for increased L/D per aircraft, and hence improved fuel efficiency, with a relatively modest potential cost. Mid term solutions involving distributed sensors and actuators to accomplish active flow and/or separation control show a great deal of promise, and require a relatively small R&D investment. Major wing redesign, in a similar time period, also shows promise. In the far term, revolutionary aircraft configurations that are significantly different from current transport/tankers could yield significant improvements in fuel efficiency, yet there will be significant costs associated with a transition to these new configurations.

Structures/Materials Solutions. Reduced structural weight has a lesser impact overall on air vehicle range, hence the study did not explore these technology solutions as extensively as in other areas. In the near term, integrated vehicle (structural) health monitoring could have a small impact on fuel efficiency while providing improved mission reliability and lowered maintenance costs. In the mid and far term, active wing load control, in conjunction with structural design and optimization procedures, and advanced design and analysis tools for overall reduced aircraft dry weight have potential for improvements in the fuel efficiency arena.

Operational Solutions. While the present study focused on technological solutions for the aircraft fuel efficiency problem, the study was made aware that there are also operational issues that could impact aviation fuel utilization. In the near term, very simple solutions that could have significant impact include expansion of Air Force tracking and reporting of fuel utilization (by bases, major commands, etc.). Similarly, if practices now routinely done by US airlines are implemented in AF aircraft operations, further reductions in fuel utilization would be possible. These practices include engine-out taxi, reduction/optimization of use of the aircraft's auxiliary power unit (APU), optimization of route planning to account for winds and weather (for drag reduction), and reduction of the vertical separation minimum between multiple (transport or other) aircraft flying a similar path. Increased use of simulators, particularly in the context of Distributed Mission Training (DMT) utilizing a range of aircraft types, could also be promising. In the mid term, the development and implementation of systems and controls for

autonomous formation flight of aircraft could have an appreciable effect on fuel efficiency and bears further exploration.

Alternative Fuels. While utilizing alternatives to crude oil-based fuels may not directly impact the “fuel efficiency” of a given vehicle to any significant extent, the fuel efficiency study views the development of alternative fuels to be of critical importance to the Air Force (and in fact, to the DoD and to the nation), since these fuels can be produced domestically and are therefore a relatively secure supply. Hence the present study did explore, in a limited way, potential alternative fuels that could be used in air vehicles in particular. The study finds that the most promising of the potentially near term alternative fuels is liquid hydrocarbon fuels extracted from coal via Fischer-Tropsch (F-T) processing. F-T fuel processing has numerous advantages: it has been known and utilized by other countries (notably South Africa) for many years, the U.S. has vast coal stores for production of such fuel, and F-T fuels are very similar to current aviation fuels in their thermofluid and combustion characteristics. Differences and challenges in using F-T fuels directly (e.g., in potential elastomeric degradation and lubricity problems) could be overcome through additives and/or blending with conventional aviation (and other) fuels. The study views F-T fuels as an extremely promising near term alternative fuel solution. In the mid term, other hydrocarbon fuels, e.g., those extracted from shale or tar sands, or those synthesized from organic materials (biodiesel, ethanol, etc.) also show some promise, but less directly for aviation fuel replacements. The study views hydrogen as a fuel source to be much less promising, at least in the near or mid term, from an economic, thermodynamic, and logistical perspective. If hydrogen ultimately can be produced such that there is a positive extractable energy balance, it does have promise in the mid-to-far term if used in fuel cells for auxiliary power units. The relatively low energy density (on a volume basis) for hydrogen makes it less suitable as a replacement aviation fuel.

Summary

This study on aircraft fuel efficiency presents a variety of findings and recommendations concerning potential technological solutions for the growing energy utilization problem, which of course exists not only within the Air Force and the Department of Defense, but nationwide and worldwide. Among the recommendations, perhaps the most critically important at this point in time are those associated with the development of alternative fuel (and energy) sources to those derived from crude oil. The lack of U.S. energy independence is clearly an issue that impacts our country economically and politically, and in large measure it is one that impacts the country’s national security and the ability to carry out missions related to national defense. In the strongest possible terms, this fuel efficiency study recommends sustained investments in the exploration, development, and introduction of alternative energy sources for the future of the Air Force and for the United States.

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Annotated Brief

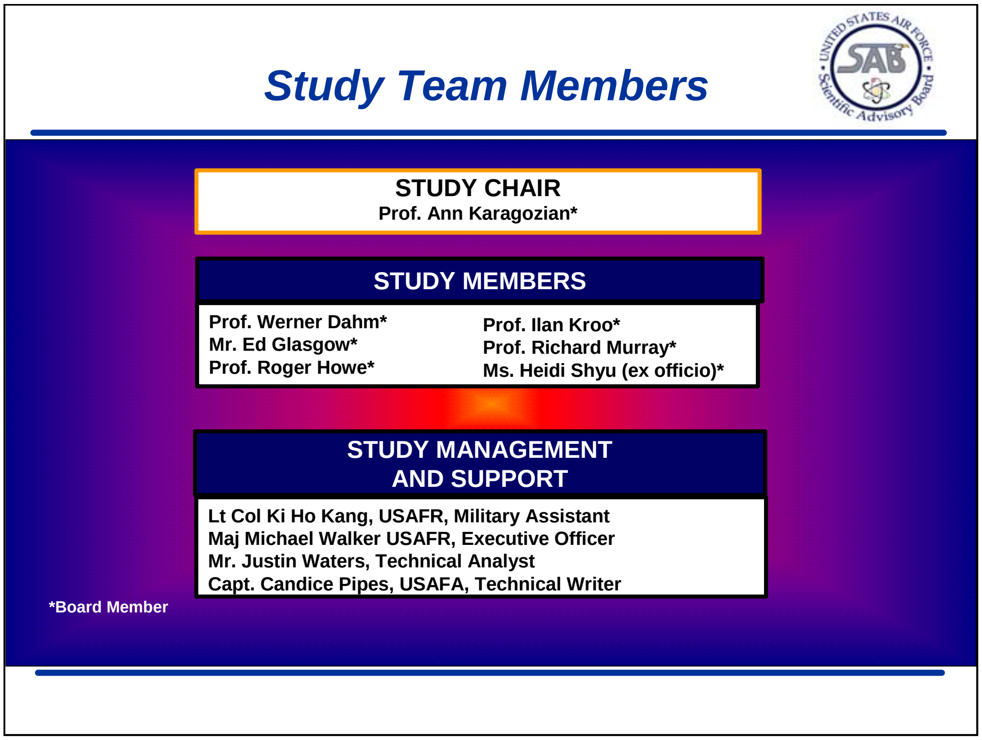
Air Force Scientific Advisory Board

TECHNOLOGY OPTIONS FOR IMPROVED AIR VEHICLE FUEL EFFICIENCY

A "Quick Look" Study

Prof. Ann Karagozian, Chair

The U.S. Air Force Scientific Advisory Board conducted a "quick look" study on the subject of **Technology Options for Improved Air Vehicle Fuel Efficiency**. The study was undertaken in the November 2005 - January 2006 time frame. The study's outbrief charts, with facing page text in addition to backup charts, are provided as follows.



This "quick look" study on Technology Options for Improved Air Vehicle Fuel Efficiency (heretofore called the "fuel efficiency" study) was conducted by a relatively small group within the Air Force Scientific Advisory Board (AF SAB). The membership consisted of seven SAB members, including the SAB Chair, Ms. Heidi Shyu, in an ex officio capacity. The group included representation from academia as well as industry:

- Prof. Ann Karagozian, Study Chair (University of California, Los Angeles)
- Prof. Werner Dahm (University of Michigan)
- Mr. Ed Glasgow (Lockheed-Martin Aeronautics Company)
- Prof. Roger Howe (Stanford University)
- Prof. Ilan Kroo (Stanford University)
- Prof. Richard Murray (California Institute of Technology)
- Ms. Heidi Shyu, ex officio, Chair, AFSAB (Raytheon Company)

Specific departmental and institutional affiliations for the members may be found in **Appendix B** of this report. The study was ably and expertly assisted by Lt. Col. Ki Ho Kang, Maj. Michael Walker, Capt. Candice Pipes, and Mr. Justin Waters of the SAB. The study team is indebted to these individuals for their dedication and hard work.

Outline

- Terms of Reference and "Quick Look" Study Scope
- Background
  - Fuel Utilization in the US, DOD, Air Force
  - Air Vehicle Efficiency/Performance Trades, Trends
  - Relevant Govt. R&D Programs
- Findings
  - Technological solutions
- Recommendations

The outline of the SAB fuel efficiency study report is shown. The terms of reference, tasking, and scope of this "quick look" study will be provided. Then a series of background charts will discuss the current state of fuel utilization within the United States, the Department of Defense, and specifically within the U.S. Air Force, providing a motivation for the present study's focus on air vehicle fuel efficiency issues. Basic definitions of air vehicle fuel efficiency-related parameters will be provided, in addition to relevant performance trades and trends over the past several decades. A brief summary of government-supported research and development programs relevant to aircraft fuel efficiency is also provided.

The findings of this study, including use of a metric for comparison among alternative solutions, will then be presented. Comparisons are made among different technologies or operationally-oriented solutions that could impact air vehicle fuel efficiency. In addition, a discussion on alternative aviation fuels is presented. Transition from crude oil-based hydrocarbon aviation fuels to these alternative fuels may not have a significant impact on the fuel efficiency of an aircraft, but the transition could have a profound impact on the DOD's access to an assured fuel source for warfighting capabilities. Finally, recommendations for an Air Force fuels technology strategy, targeting concepts that are and could become viable in the near-, mid-, and far-term are provided.

1. Terms of Reference and "Quick Look" Study Scope

Tasking / Terms of Reference

- **Assess the problem: What are the problems, issues, and major culprits in Air Force fuel/energy utilization?**
- **Assess what's been done: What are the relevant benefits of recent government propulsion performance/efficiency programs?**
- **Assess potential immediate concepts: What can be done today that could have an impact?**
- **Assess potential solutions: What are the promising current/future technologies that could impact fuel efficiency?**
- **Recommend potential near, mid, and far term solutions**

"Quick Look" at potential SCIENTIFIC and TECHNOLOGICAL solutions

The Terms of Reference (TORs) and tasking for this quick look study are summarized in this chart; the actual TORs are provided in **Appendix A**.

The fuel efficiency study members were asked to "assess the problem," i.e., to broadly identify the problems and shortcomings in Air Force (and DoD/U.S.) fuel and energy utilization and to identify the critical need areas. The study was tasked with assessing the relevant benefits of government investment programs that have been directly (or indirectly) aimed at improving aircraft fuel efficiency. The fuel efficiency study was asked to assess and explore the trade space that exists for alternative technology solutions, i.e., to assess the strengths and weaknesses that each may bring to the table. Finally, on the basis of this technical assessment, the fuel efficiency study was asked to recommend technology development strategies for fuel efficiency that could be employed by the Air Force for possible implementation in the near-, mid-, and far-term.

An overriding feature of the present study is a focus on potential scientific and technological solutions that could impact fuel efficiency within the Air Force.

FE Study Briefings, Other Input

USAF
AFRL/PR
AFRL/VA
AFRL/VA
HQ AMC
AFOSR
EOARD
AF/IL
SAF/FM

Other Govt./FFRDCs
NASA
FAA
OSD/DOE Assured Fuels Init.
Rand Corp.
Sandia Natl. Labs

Industry (engine cos.)
Pratt & Whitney
General Electric
Rolls Royce
Honeywell

Industry (airframe/integ.)
Boeing
Lockheed-Martin
Northrop-Grumman
Aviation Partners

Industry (airlines, oil)
British Petroleum
Intl. Air Transport Assn.

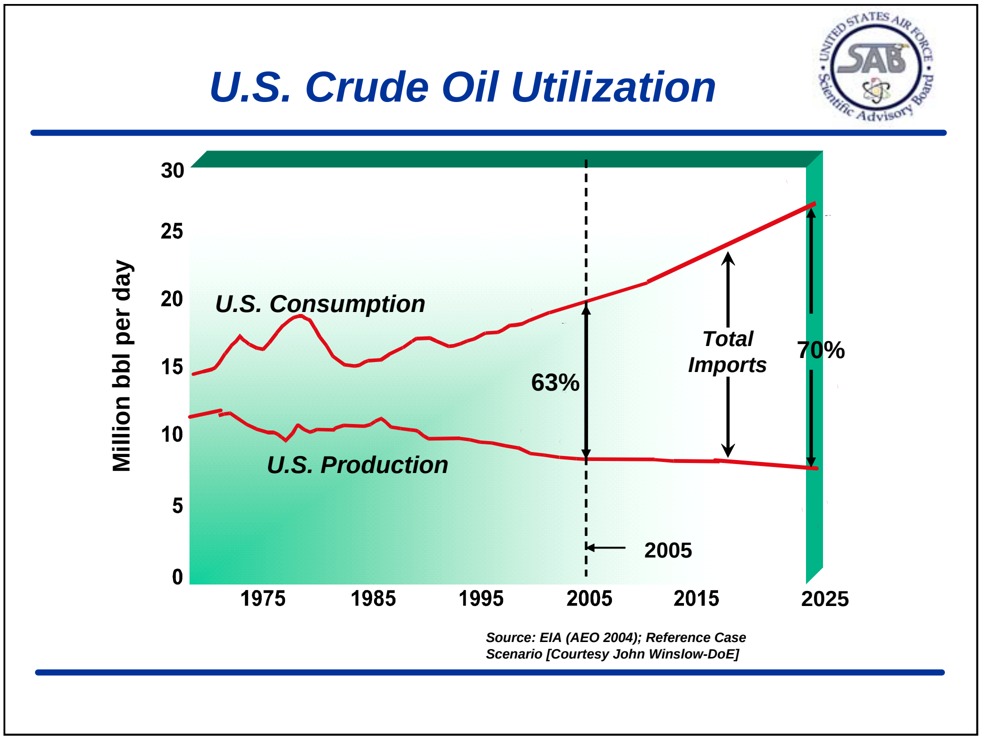
Universities
MIT

COLOR CODING:
Aerodynamic concepts
Engine/component concepts
Alternative fuels
Overviews, operational issues

In the course of this "quick look," the fuel efficiency study received briefings or report documents from a relatively large number of different groups, not only within the Air Force, but also from other DoD and government agencies, from industry, and from academia. Many of the briefings and reports focused on specific types of technology concepts, as indicated by the color-coding above (red for aerodynamic concepts, green for engine or engine component concepts, and blue for alternative fuels). Other briefings and reports either concerned broader assessments of fuel efficiency in the Air Force and/or operational issues that could impact fuel efficiency. These are shown in black.

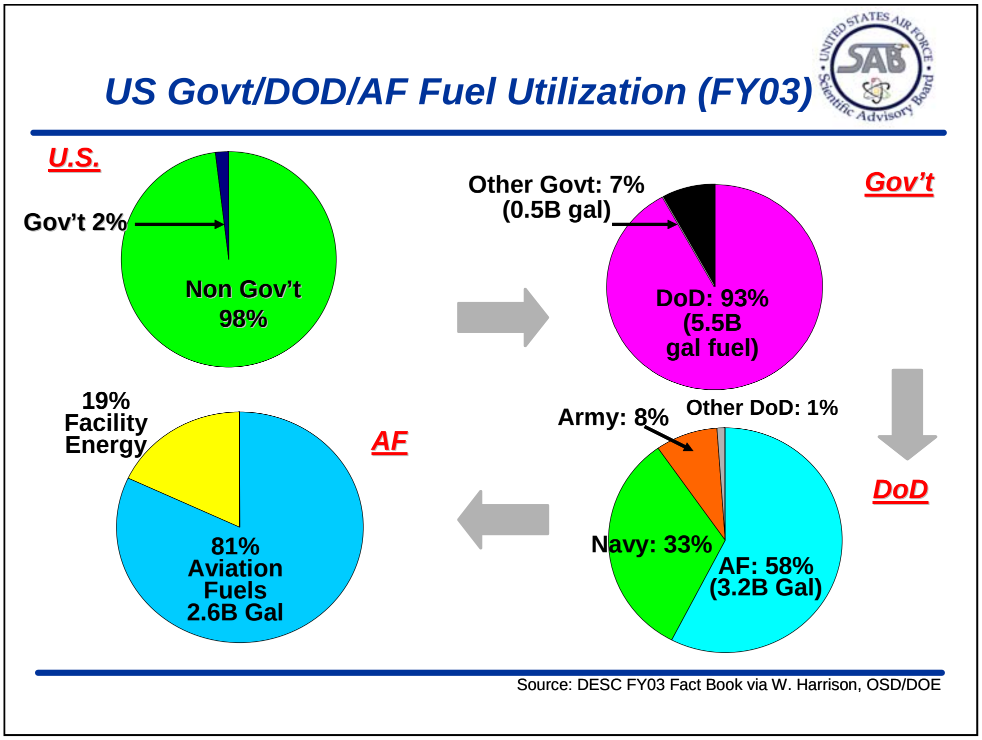
A listing of the contributing organizations is also included in **Appendix C.**

2.1. Background: Fuel Utilization in the U.S., DoD, and Air Force



An important trend within the United States that affects the Department of Defense is the increase in U.S. consumption of fuels derived from crude oil and the simultaneous decrease in U.S. production of crude oil that has occurred over the last decade, as shown above. In 2005, the U.S. imported 63% of the crude oil it consumed overall; approximately 16% of this is currently imported from Canada, 13.4% from Saudi Arabia, 12.6% from Mexico, 12.4% from Venezuela, 7% from Nigeria, and 5% from Iraq, as indicated by the U.S. Department of Energy [**http://tonto.eia.doe.gov/dnav/pet/pet_move_impcus_a2_nus_ep00_im0_mbbl_a.htm**]. Over the next 20 years, it is predicted that this import fraction will rise from 63% to 70%, exacerbating the United States' dependence on foreign sources of energy.

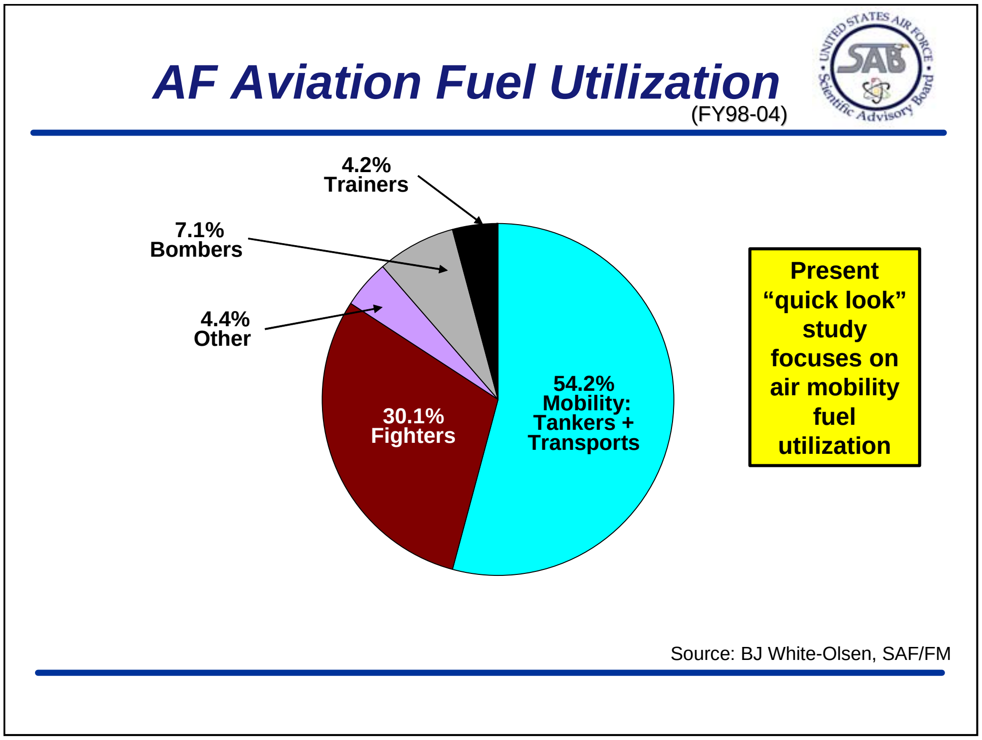
Furthermore, given the rising demand for energy from Asia and other developing regions of the world, one can anticipate that the price of oil will continue to rise substantially in the future and continue to be the source of geopolitical tension. For example, while oil consumption in the United States is expected to increase over the next decade at an annual rate of about 1.5 percent, oil consumption in China is forecast to grow at almost 6 percent per year [**Ref.**: *International Energy Outlook 2005*, Washington, DC: Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, July 2005, **http://www.eia.doe.gov/oiaf/ieo/pdf/0484(2005).pdf**]. Thus it is likely that competition for petroleum resources will continue to increase and will remain a catalyst for conflict.



Of the fuel from crude oil consumed by the United States, only about 2% is attributed to government consumption (e.g., during FY03, as shown in the upper left pie chart). Yet the government has the capability to catalyze large scale change with respect to energy generation and utilization through strategic technology investments across a number of areas and agencies, as will be seen.

While the government constitutes a small consumer with respect to fuel/energy usage within the U.S., the Department of Defense (DoD) accounts for about 93% of the overall government consumption of fuel from crude oil, or 5.5 billion gallons of fuel per year (upper right). Further, of the total DoD fuel usage, the Air Force is the largest single user at 3.2 billion gallons of petroleum-based fuel per year (constituting 58% of total DoD usage, shown in the lower right pie chart). Hence improvements in fuel efficiency and utilization by the Air Force can have a significant impact on the DoD's fuel consumption and associated fuel costs. Moreover, of the Air Force's overall fuel consumption, aviation fuels represent the largest fraction by type consumed, at 81% (2.6B gallons/year, shown in the lower left chart). By its utilization of aviation fuel, the AF as an entity actually ranks about fourth in the nation, behind the three largest U.S. airlines.

Understanding these statistics helped to focus the present "quick look" study on the area that potentially could have the biggest impact for Air Force energy savings: that associated with **Air Force utilization of aviation fuels**.



As shown in the figure above, the largest single fraction of Air Force aviation fuel usage is for mobility operations: tankers and transports. These data, based on number of gallons of fuel consumed by the vehicle itself (not, for example, including fuel off-loaded from a tanker to a fighter aircraft), represent aviation fuel utilization averaged over FY 98-04. Mobility aircraft are substantially similar to commercial aircraft, and the requirements with respect to military factors (stealth, maneuverability, etc) are less extreme. In addition, mobility aircraft are subsonic vehicles. Because tankers and transports constitute the largest fraction of aviation fuel consumers in the Air Force, the present study focused somewhat more exclusively on fuel efficiency issues relevant to large subsonic mobility aircraft.

We note that these data are not automatically and widely disseminated by the AF on a regular basis, but are available on demand. Each AF base does track this information, for example, and various commands track fuel, since they pay for it. It is possible that even the level of fuel dumping is regularly quantified, but our study was not able to find this information.

"Fully Burdened" Cost of Fuel

- **Actual cost of fuel (DESC price to AF):** **$2.14/gal**
- **Cost to transport fuel via tanker:** **$24.23/gal**
- **Total Cost:** **$26.37/gal**

Need to account for "fully burdened" cost of aviation fuel when comparing benefits of alternate solutions

Source: BJ White-Olsen, SAF/FM

The previous chart cites AF aviation fuel utilization according to gallons of fuel consumed (which is roughly proportional to the dollars spent on the fuel itself). Yet the "fully burdened" cost of fuel accounts not only for the actual cost of the fuel to the Air Force (purchased through the Defense Energy Supply Center or DESC), but also for the cost of transporting the fuel overseas and delivering it via tanker. The data shown above suggest that if one were to fill a gallon of aviation fuel into an AF aircraft in CONUS (in late 2005), it would cost $2.14 to the AF, but for a tanker to transport the fuel overseas and deliver it to another airborne platform, one needs to add another $24/gal to account for infrastructure, personnel, and other costs associated with the transport. A 2001 Defense Science Board study [**"More Capable Warfighting through Reduced Fuel Burden: Findings of the DSB Task Force on Improving Fuel Efficiency of Weapons Platforms," January, 2001**] recommended that the DoD base investment decisions on the "true cost of delivered fuel" rather than "relying on the low DESC standard fuel price."

In exploring and comparing alternative technologies for improved aircraft fuel efficiency, the present study kept in mind this "fully burdened" cost of fuel, although no serious cost analysis was performed to any extent in the study. We recognize that these alternative technologies ostensibly could impact just the utilization of the fuel itself, and that it is possible that the additional costs added to the fuel price (e.g., the air refueling tanker fleet) are mostly fixed and should be evaluated on a case by case basis for each re-engining study. But widespread fuel savings in principle should have at least an indirect impact on the $24/gal cost as well; it is just not clear how, and how much. The SAB study believes that quantifying the changes in indirect fuel costs with more efficient air vehicles should be made with validated requirements models.

2.2. Background: Air Vehicle Efficiency/Performance Trades & Trends

Contributors to Fuel Efficiency

Distance traveled for given amount of fuel:
Breguet Range Equation

$$\text{Aircraft Range} = \frac{\text{Velocity}}{\text{TSFC}}\left(\frac{\text{Lift}}{\text{Drag}}\right)\ln\left(1+\frac{W_{fuel}}{W_{PL}+W_{O}}\right)$$

• Engine Fuel Consumption

• Aerodynamics

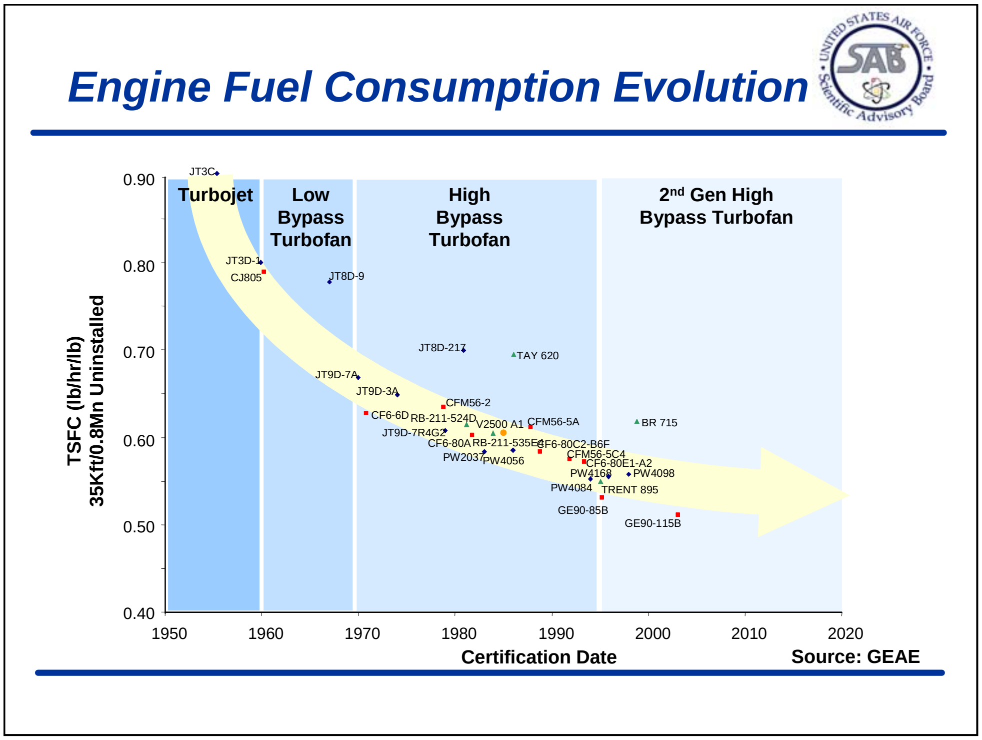
• Structural Weight

Thrust Specific Fuel Consumption TSFC = fuel flow rate/Thrust

W_{fuel} = **Fuel Weight**
W_{PL} = **Payload Weight**
W_{O} = **Dry Weight or "Operating Empty Weight" (OEW) of Vehicle**

The technological contributors to aircraft fuel efficiency are best understood by examining the classic "Breguet Range Equation" shown above, which quantifies the approximate distance ("range") an aircraft can travel under cruise conditions, at a given velocity, for a given amount of fuel (with weight W_{fuel}) and with a given payload (with weight W_{PL}). Note that the logarithmic term in brackets represents the initial aircraft weight divided by the final weight, after the fuel has been completely consumed.

One can increase the aircraft range for a fixed amount of fuel and payload by reducing the Thrust Specific Fuel Consumption, TSFC, which is the rate (on a weight basis) at which fuel flows into the engine divided by the thrust delivered by the engine to the vehicle. TSFC has units of inverse time. One could also increase range by improving the Lift-to-Drag ratio (L/D), which is largely dependent on the aerodynamic design of the vehicle. Finally, one could also increase aircraft range by reducing the "dry" structural weight (W_O or OEW, the Operating Empty Weight) of the aircraft itself. We also note that aircraft velocity impacts range, not only as shown in the equation above, but also indirectly (and non-trivially) through the TSFC and L/D terms. Hence from a technological perspective, improving aircraft fuel efficiency is largely accomplished through improvements in the engine design, aerodynamic design, and structural design of an aircraft.



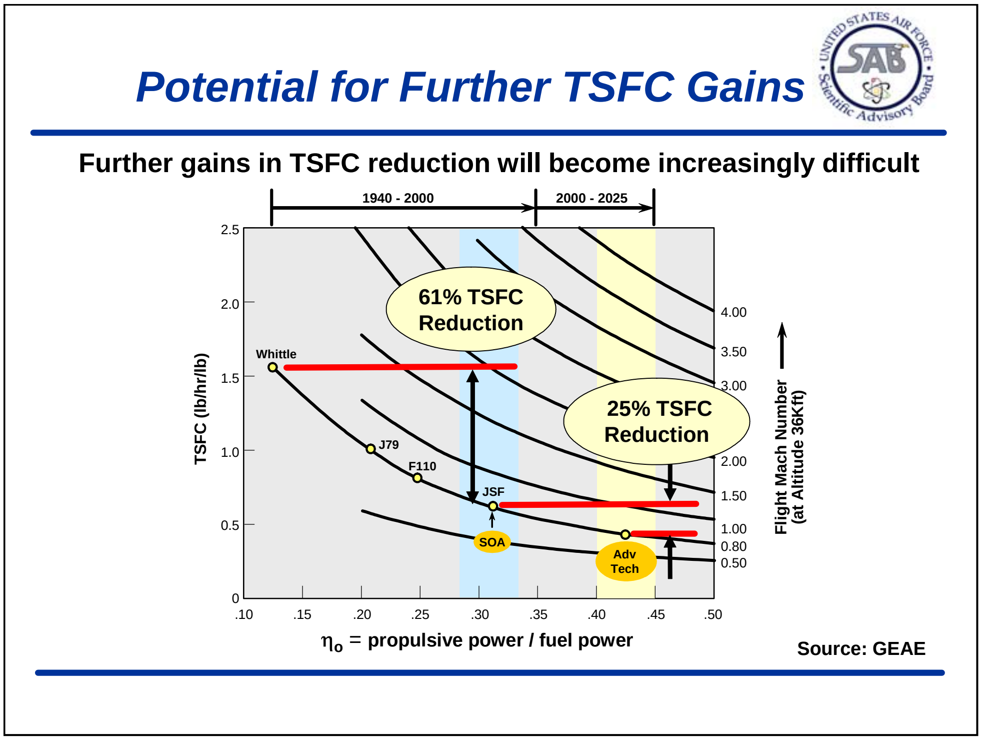
Over the past few decades, technologies introduced in gas turbine engines have led to substantial improvements in aircraft fuel efficiency. Since TSFC is the fuel consumption rate in lbs/hr divided by the engine thrust in lbs, low TSFC values represent more fuel-efficient engines. Trends in TSFC reduction for various engines and engine classes since the 1950s are shown in the chart above. While the engines shown are generally used on commercial aircraft, there are similar military versions of many of the engines shown. For example, the GE CFM56-2 is the commercial version of the military F108 engine, flown on the KC-135R; the PW JT3D is the commercial version of the TF33 engine, flown on the B-52, KC-135E, and C-141 aircraft; the GE CF6 was evolved from the TF39, used on the C-5 aircraft, and the PW 2000 is the commercial version of the F117 engine, flown on the C-17. The GE90-115B is a new engine which recently completed a successful flight demonstration on the Boeing 777.

These reductions in TSFC came from three main factors: (1) increases in the bypass ratio (BPR), (2) increases in the turbine (rotor) inlet temperature (TIT), and (3) increases in the overall pressure ratio (OPR). The single largest benefits have come from increasing the bypass ratio, namely the ratio of the air flow bypassing the turbojet core of the engine to the air flow entering the core. For the same thrust, increasing BPR increases the propulsive efficiency part of the overall engine fuel efficiency, and thereby reduces TSFC. Since 1950, TSFC has been reduced significantly through the shift from pure turbojets to low and high bypass turbofans and to current state-of-the-art high bypass turbofans such as the PW4000, GE90, or RR Trent 895, which have BPR's as high as 9.0.

Military air tankers and transport aircraft typically have simple under-wing engine configurations and use high-BPR engines to achieve high fuel efficiency comparable to commercial aircraft. Further reductions in TSFC on such air mobility aircraft can come from

increases in TIT and OPR, though the fuel efficiency gains are becoming increasing smaller as these technologies mature.

The propulsion systems for fighter aircraft face different constraints than do commercial aircraft. Advance fighters have stringent performance requirements for maneuverability, low observable (LO) characteristics, high speed dash, etc. that demand engines with high thrust-to-weight and aircraft with low transonic/supersonic drag levels. Such engines have a relatively low BPR and are usually deeply buried within the aircraft fuselage. Engines such as the F119/F135 in the F-22 and F-35, respectively, have BPR's below 0.5. In such engines, the bypass air is used more for cooling than for propulsive efficiency, and as a result the TSFC values are substantially higher than for state-of-the art commercial aircraft engines.

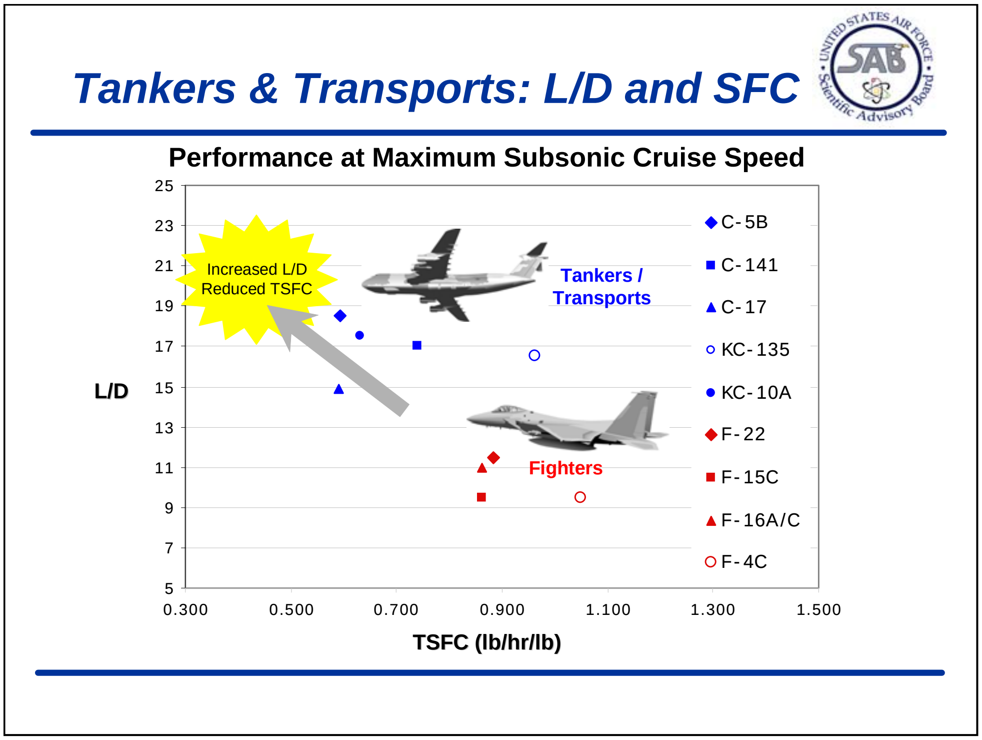


Since fighters and bombers that require deeply integrated propulsion systems cannot use high bypass ratios to achieve reductions in TSFC, this chart shows improvements in TSFC and overall efficiency achieved over the past 60 years in low bypass ratio engines, as well as future reductions that can be expected from advanced technologies.

The overall engine efficiency, η_o, namely the propulsive power produced per unit fuel power supplied to the engine, is inversely proportional to TSFC through the flight speed and specific energy of the fuel. Because flight speeds and fuels for military aircraft have changed over the past 60 years, the five low bypass engines shown here have been scaled to the same flight speed and fuel type, to allow direct comparison of their fuel efficiency. Each curve is for a different flight speed expressed as flight Mach number at 36,000 ft. altitude. The five engines shown have been scaled to Mach 0.80.

From Whittle's first gas turbine aircraft engine in 1941 to the state-of-the-art F135 engine in the F-35 Joint Strike Fighter (JSF), TSFC has decreased by 61%. This represents a factor of 2.5 increase in overall engine efficiency, from 0.12 in 1941 to 0.31 in the JSF. The improved fuel efficiency has primarily come from numerous incremental technologies that increased the rotor inlet temperature and overall pressure ratio of gas turbine engines.

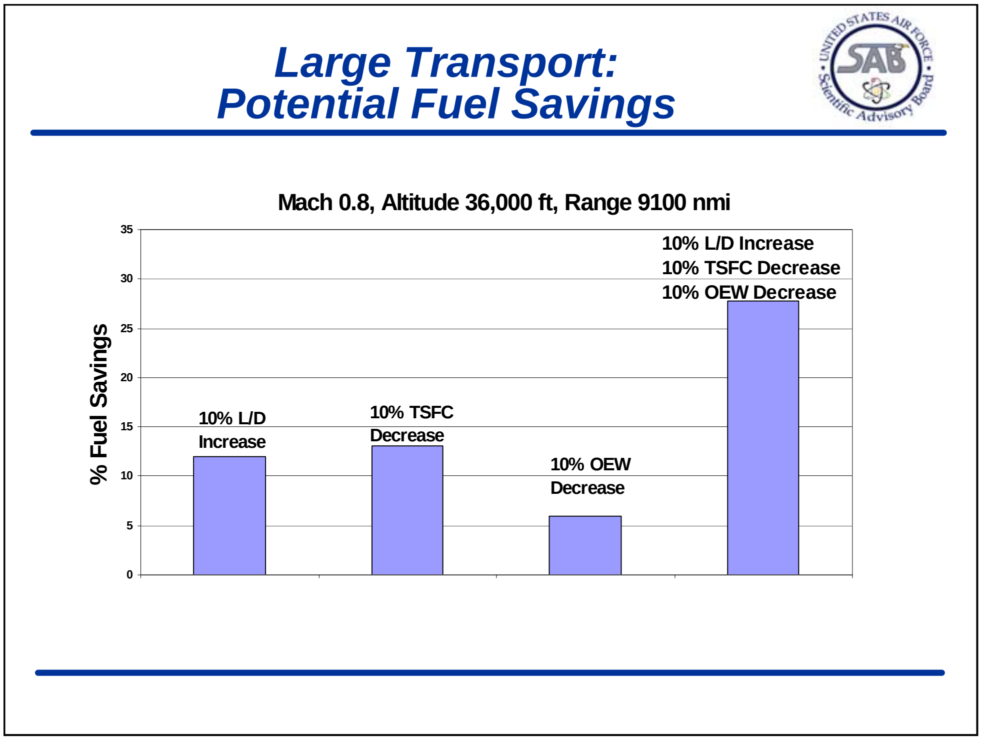
For such low bypass engines, gains in TSFC are becoming increasingly difficult. Industry estimates of the combined effect of future technologies for increasing TIT and OPR show a reduction in TSFC for low bypass engines of 25% over the current state-of-the-art. This represents a 37% increase in overall engine efficiency, to about 0.42. Even for air mobility aircraft with high bypass engines, future improvements in fuel efficiency will come as much from improved aerodynamics, structures, and operations as from the propulsion system itself.



Increasing aircraft lift-to-drag ratio (L/D) and reducing engine thrust-specific fuel consumption (TSFC) lead to improved fuel efficiency, as noted earlier. This chart indicates, for different types of aircraft (tankers/transports in blue and fighters in red), the approximate L/D ratio and TSFC at maximum subsonic cruise conditions. Specific values of the Mach number at which these conditions are represented are as follows (obtained from AFRL/PR):

Aircraft	Mach number at max cruise cond.	L/D	TSFC (lb/hr/lb)
C-5B	0.78	18.8	0.59
C-141	0.73	17	0.73
C-17	0.77	14.9	0.589
KC-135	0.76	18	0.947
KC-10A	0.8	17.2	0.63
F-22	0.85	11.8	0.898
F-15C	0.85	9.5	0.876
F-16A/C	0.85	11	0.876
F-4C	0.85	9.5	1.07

Performance requirements for fighters, including maneuverability, low observable (LO) characteristics, high speed dash, etc., result in lower L/D and higher TSFC than that of typical transport aircraft, as shown in the figure. Constraints on some transport aircraft also reduce fuel efficiency. Requiring short take-off and landing distances or limiting wing span, for example, directly affect aircraft design, generally resulting in lower cruise efficiency. For supersonic aircraft, the extra drag associated with shock waves reduces efficiency, resulting in supersonic L/D values that are less than half of what might be achieved for a subsonic aircraft.

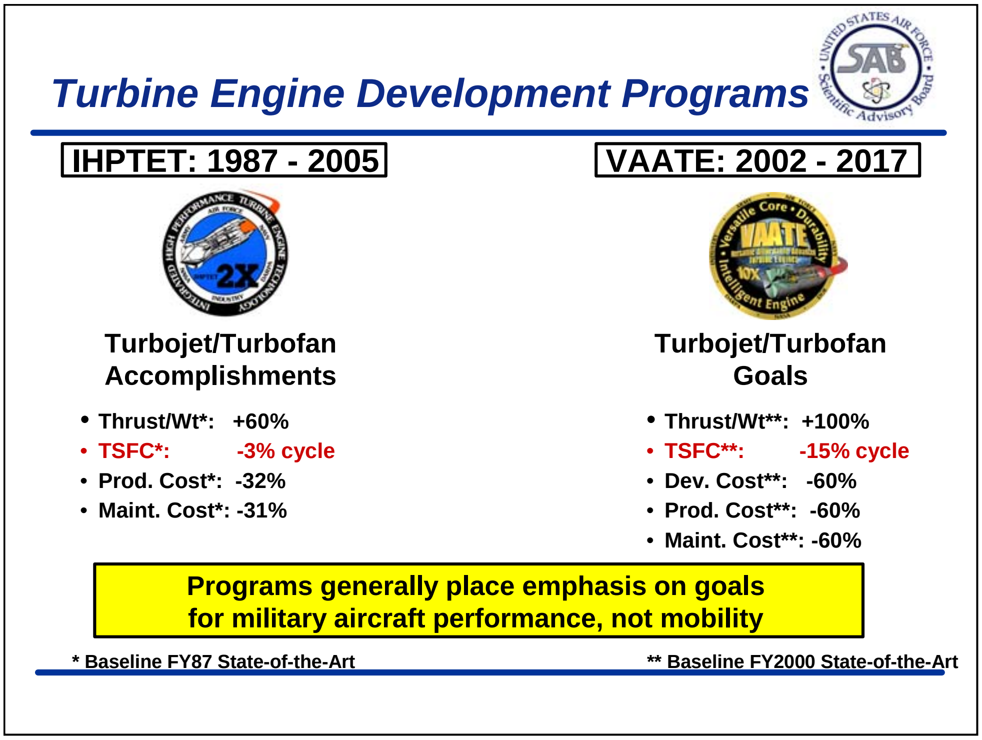


This chart indicates the possible savings in fuel that can be attained by separate, independent improvements in L/D, TSFC, and OEW for a large transport operating at a typical cruise condition of Mach 0.8 and altitude of 36,000 feet. A 10% increase in L/D, a 10% decrease in the TSFC, and/or a 10% decrease in OEW are considered here. The fuel savings sensitivity to each of the three parameters is illustrated by varying the parameters separately and then as a combined total.

The fuel savings calculations were made using the Brequet Range equation performance data associated with a large transport, e.g., the C-5 A/B. The ferry range was fixed at 9100 nmi, and the change in fuel weight, W_{fuel}, for a fixed payload weight, $W_{PL,}$ and fixed flight velocity was calculated for the improvements in L/D, TSFC, and OEW noted above. With a 10% reduction in TSFC, one achieves a 13% fuel savings (i.e., a reduction in W_{fuel} by 13%). A 10% increase in L/D leads to 12% fuel savings, and a 10% reduction in dry weight or OEW leads to a 6% increase in fuel savings. Since the OEW appears as a logarithmic term in the Brequet Range equation, it has less impact on fuel savings than either L/D or TSFC.

A very significant overall fuel savings of 28% can be realized by improving all three parameters by just 10%, shown in the right-most column. Note that if one omits the effect of the OEW reduction, the percentage fuel savings derived from L/D and TSFC improvements is 23%, which is still substantial.

2.3. Background: Relevant Government R&D Programs



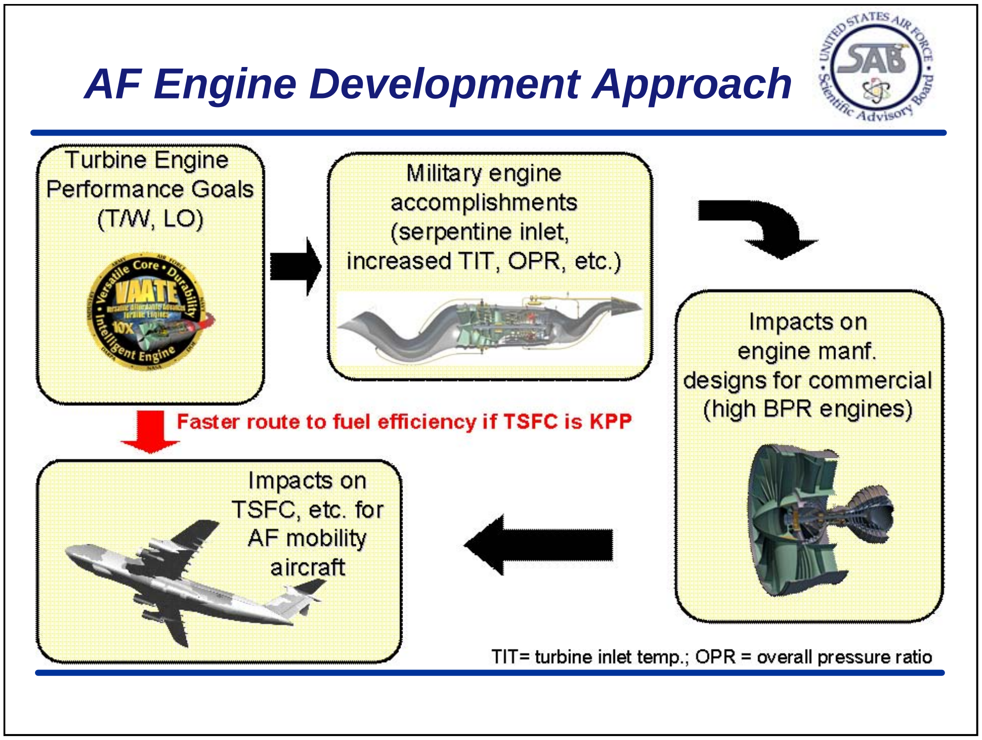
A number of government-industry funded programs over the years have aimed at accelerating technological developments for turbine engines for propulsion systems.

The **IHPTET** (Integrated High Performance Turbine Engine Technology) program ran from 1987 until 2005 and was a partnership among various DoD, NASA, and industry organizations. IHPTET had a number of specific goals and milestones for engine development, mainly with respect to KPPs (key performance parameters) associated with military engines. In terms of turbofan/turbojet engines, thrust-to-weight ratio improvements were on the order of 60%, with over 30% reductions in production and maintenance costs. Among the other specific goals were improvements in combustor inlet temperature (T3), which resulted in a 50^{o}F T3 increase; this translated into a 3% reduction in the TSFC. It is this study's understanding that there were no specific KPPs with respect to fuel efficiency for IHPTET. Many of the IHPTET technologies have been or are in the process of being implemented into the F119 engine on the F/A-22, the F414 engine on the F-18E, and the AE 3007H engine for Global Hawk.

The **VAATE** (Versatile Affordable Advanced Turbine Engines) is an ongoing, ambitious turbine engine program, again a partnership among DoD, NASA, and industry, which was initiated in 2002. VAATE has had significant budget cuts in the last several years; these cuts have severely impacted industry's contributions to the program in particular. VAATE also has specific goals for KPPs, and, in contrast to the IHPTET program, has specific goals for TSFC reduction (15% cycle reduction). In addition, while IHPTET focused on the core engine,

VAATE's focus is on optimizing the performance of the entire propulsion system, including inlet, core, and nozzle.

Beyond these partnership programs, a new **ADVENT** (Adaptive Versatile Engine Technologies) program has been proposed by AFRL/PR with the goals of actively controlled, optimized propulsion systems to achieve short takeoff distances, rapid climb/acceleration, loiter persistence, efficient subsonic and supersonic cruise, high combat maneuverability, high power extraction, and enhanced survivability.



The study members observed from various presentations that the typical development approach for new AF engines appears to be as follows. Programs such as VAATE have specific goals with respect to Key Performance Parameters, but these are largely aimed at fighter aircraft (e.g., thrust-to-weight or T/W, high angle-of-attack performance, and low observable or LO performance). Yet TSFC and other parameters related to fuel efficiency are usually not KPPs. The performance goals drive new technology for military engines and often result in configurations specific to high performance aircraft, e.g., serpentine inlets for LO requirements, increased turbine inlet temperature (TIT or T4), increased overall pressure ratio (OPR), etc. These technologies, initiated within government laboratories such as AFRL but developed by industry, ultimately can have an impact on commercial engines, which typically are high bypass ratio (BPR) turbofans as shown. Advances for the commercial engines eventually find their way into TSFC reduction for AF tanker and transport aircraft engines, which are also high BPR turbofans. But the technology development route for such fuel efficiency improvements can be longer and relatively circuitous.

An alternative approach in engine technology advancements that could impact fuel efficiency more rapidly (red arrow above) might be to directly target improvements for high bypass ratio engines (which would then benefit both military mobility aircraft and commercial aircraft). With TSFC and other fuel efficiency-related quantities as Key Performance Parameters, the engine development cycle would have a faster route to energy efficiency. We note that one engine program, ADVENT (described on the prior page), proposes to have advanced development BOTH from the point of view of fuel efficiency (lowered TSFC requirements) for cruise and loiter conditions as well as from the point of view of military performance (T/W, T/airflow requirements) for takeoff, acceleration, climb, and combat conditions. Many of the ADVENT technological advances are proposed to take place through

adaptive engine flow control methodologies, building on AFRL basic and applied research activities.

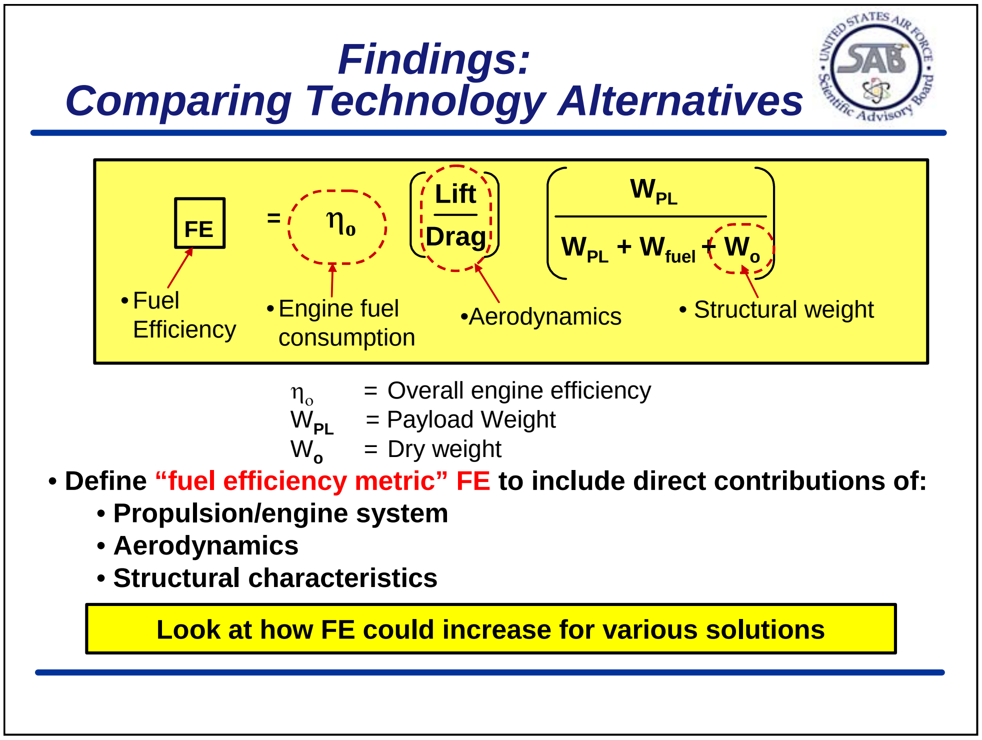
Other Govt. Aeronautics Programs

- **NASA Aeronautics, FY00-05**
  - **Focus on emissions, noise reduction, engine control**
  - **Ultra Efficient Engine Technology (UEET) ~ FY00-FY05**
    - **Achieved 15% CO2 Reduction for subsonic transports (thus 15% reduction in overall fuel burn)**
    - **Focus on NOx reduction can work against fuel efficiency**
  - **NASA Aeronautics program currently undergoing significant re-formulation**

NASA has long played a major role in advancing the state-of-the-art in gas turbine engines, with the primary motivations being mitigation of the environmental impacts of civilian air transportation through reducing CO_2 and NO_x emissions and noise. The Ultra-Efficient Engine Technology (UEET) program, for example, which lasted from 2000 through 2005, identified technologies with promise for meeting these goals. Flow control and turbine aerothermal technologies, as well as higher loading, were the approaches with the largest impacts on fuel burn reduction. A reduction of about 15% in overall fuel burn was accomplished through UEET research. We understand that NASA's continued interests in engine emissions and noise reduction are being translated into research on core aeronautics competencies in the newly announced Fundamental Aeronautics Program.

Yet over the past two years, NASA has refocused its research programs toward the challenges of returning to the moon and preparing for missions to Mars. Given the constraint of constant budgets, NASA's role in air-breathing engine research will likely decrease. Recent tensions between NASA and Congress have led to instability in aeronautics research funding and a shift in focus from demonstrators to basic research. Thus, in order to ensure that highly efficient gas turbines are developed for future transport aircraft, commercial as well as military, the Air Force must take the lead in ensuring funding continuity for applied research and development on the supporting technologies.

3. Findings: Technological Solutions



Many technologies can affect fuel efficiency, as noted previously. Improved structural design, new materials, more efficient engines, and aerodynamic advances influence aircraft efficiency in different ways. To assess and compare how various technology solutions can affect the overall engine efficiency, and to allow consideration of alternate fuels, a simple "fuel efficiency" or FE metric is defined above, as the product of the engine's overall efficiency η_o, lift-to-drag ratio, and vehicle payload fraction. The influence of propulsion, aerodynamics, and structures is explicit in this metric, which could be viewed to be a very approximate, non-dimensional estimate of the distance that a given payload weight may be transported per unit of energy in the fuel.

Note that the overall engine efficiency η_o is related to the thrust-specific fuel consumption by the relation:

$$\eta_o = V / (TSFC{*}h_f)$$

where V is the vehicle speed and h_f is the heating value of the fuel (energy per unit weight). In exploring various technological solutions and their impact on the "FE" metric, engine solutions were viewed in terms of the capability to increase η_o, aerodynamic solutions were viewed in terms of the impact on increasing L/D, and structural solutions were viewed in terms of the ability to reduce the aircraft's dry weight (or OEW), W_o.

Engine Solutions: Benefits/Cost

	Δ FE	Δ FE/Cost
• **Near term (0-5 years):**		
• Engine fan wash	1%	High
• **Mid term (5-15 years):**		
• Re-engine current fleet	15%	Medium
• New/alternative engines e.g., high BPR engines, propjets	10%	Medium
• **Far term (15+ years):**		
• VAATE techs., e.g., active control/ ultra high temperature sensors	15%	High
• Revolutionary engines (PDEs, wave rotors)	15%	Medium

Beginning with this chart, solutions are listed that are identified in this study as being the most beneficial in terms of their expected improvement in fuel efficiency relative to their very rough cost of implementation. These solutions are organized on separate charts for each technology area, and on each chart are grouped into near-, mid- and far-term implementation time periods. "Near term" is defined as the period from the present out to five years; "mid term" five to fifteen years in the future; and "far term" implement-able beyond fifteen years in the future. For each solution, both the approximate **benefit** (ΔFE, or the *change* in the "fuel efficiency" metric defined on the previous chart) and the **benefit-to-cost ratio** (ΔFE divided by a rough estimate of cost) are listed. Each technological concept identified here are those having, approximately, a "high" or "medium" impact based on the benefit-to-cost ratio. The values and magnitudes of ΔFE and benefit-to-cost are not exact here (due in part to the brevity of this "quick look" study), but should be regarded to be rough approximations. If a potential technological (or other) solution had a "low" benefit-to-cost ratio, then it was not included in the list. Finally, it should be noted that the ΔFE metric here is likely NOT additive if multiple solutions are implemented.

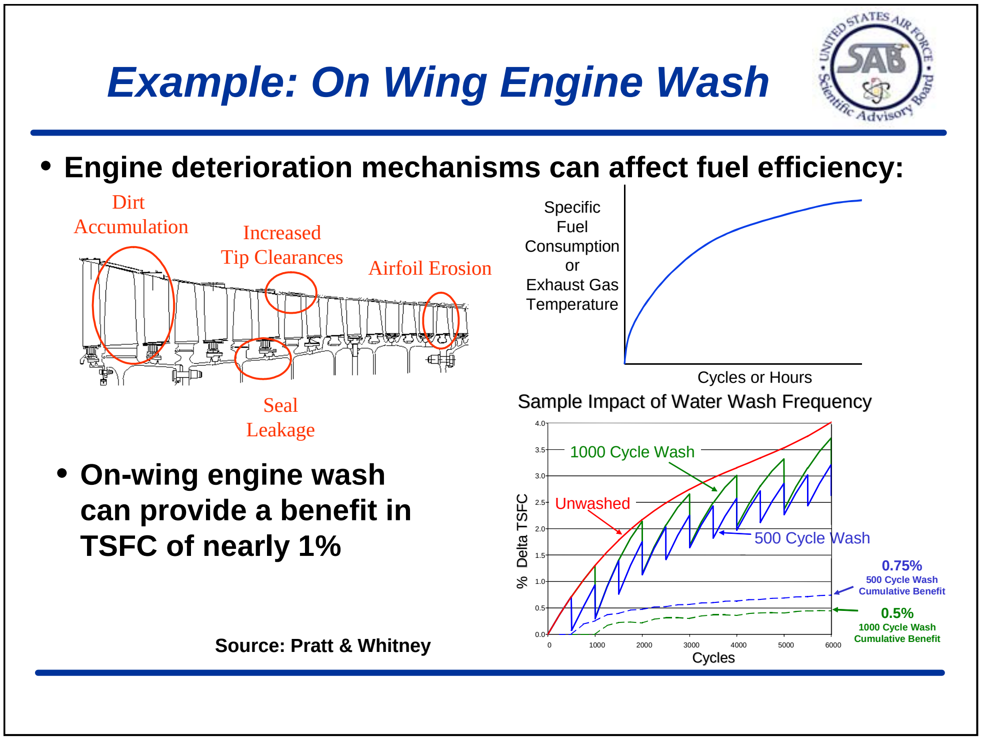
The chart above lists the solutions related to engines. With respect to improving engine efficiency, engine fan wash is a near-term solution that provides a relatively small incremental improvement in the fuel efficiency parameter, but achieves this at extremely low cost. The technology is described in detail on the following chart.

Among mid-term solutions, the study found that re-engining of existing aircraft, e.g., the 50 C-5B and 76 C-5A air transports, could increase their fuel efficiency by about 15%, but involves a relatively high cost. It is expected that re-engining of KC-135E's would have higher effective benefits (e.g., TSFC improvements on the order of 30% over existing engines), and

with comparable costs. As a result, the benefit-to-cost ratio of re-engining is estimated to provide a “medium” impact. For the later mid term period, development of derivative high bypass engines for air transports and tankers, or even turboprop engines with up to 30% improvement in fuel efficiency based on 1980’s demonstrations, may together provide 10% increase in the fuel efficiency metric, but the associated cost makes this a medium-impact solution.

VAATE, or a program like it, will be the primary mechanism for continued evolution of numerous technologies that together can have a substantial impact on engine solutions with high benefit-to-cost ratio for improved fuel efficiency. VAATE is very broad, but new sensors and active control of inlet and combustor flows are among several promising technologies to be pursued. A specific VAATE focus on fuel efficiency may produce a different mix of solutions than did the IHPTET program.

In the very far term, radically different engine types based on the inherently higher fuel efficiency of novel engines (such as detonation-based cycles or wave rotors) can provide substantial improvements over gas turbine engines. The wave rotor is being investigated for use as a core gas generator in future gas turbine engines in order to achieve high peak cycle temperatures and pressures. Detonation-based cycles such as the Pulse Detonation Engine involve periodic formation and reflection of detonation waves in a constant volume cycle, but currently have challenges with respect to noise and robust performance. These types of new engines will require further technology development and large development costs, and thus have at most “medium” impact.



Gas turbine engines undergo gradual deterioration with time that results in significant engine performance losses. The deterioration comes from several aging factors such as dirt accumulation, airfoil erosion, increased tip clearances, and seal leakage. These factors over time produce a decrease in engine fuel efficiency, as well as degradation of numerous other engine performance parameters. Complete engine overhauls are done periodically to restore an engine and recover part of this performance deterioration, but since such major overhauls are expensive they are done infrequently. Between overhauls, the deterioration of a typical twin-spool turbofan engine can lead to a 4% increase in the engine's thrust-specific fuel consumption (TSFC).

A significant part of this TSFC increase results from simple accumulation of dirt and other deposits on the fan. Early in the maintenance cycle, these fan surface deposits are the single largest contributor to the overall engine deterioration, creating a 1% increase in TSFC. Later in the cycle, other factors combine to produce larger increases in TSFC, but the 1% increase in TSFC from fan surface deterioration remains essentially constant.

A relatively simple and low-cost on-wing water wash of the fan, done at regular intervals, can remove most of the increase in TSFC due to these fan surface deposits. The chart shows the effects of such a fan wash done at intervals of 500 and 1000 engine cycles. In both cases, the fan wash removes essentially all of the increase in TSFC from fan surface deterioration. This results in a 0.75% cumulative reduction in TSFC when performed at 500-cycle intervals, and a 0.5% reduction when done at 1000-cycle intervals. Commercial airlines increasingly use fan wash to improve their fuel efficiency. A recent report by the International Air Transport Association [**"Guidance Material and Best Practices for Environmental Management, IATA, 1st Ed., Dec., 2004]** suggests that on-wing engine wash plus regular aircraft polishing can actually reduce TSFC by 1.5-2.5%.

Aerodynamic Solutions: Benefits/Cost

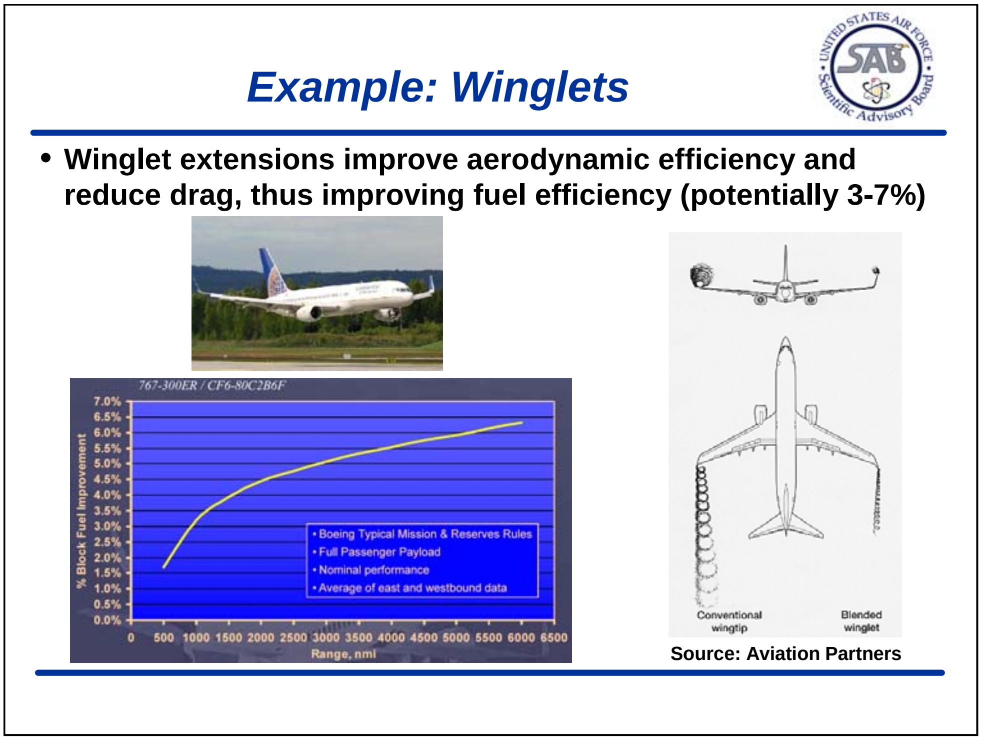
	Δ FE	Δ FE/Cost
• Near term (0-5 years):		
• Wing retrofits, e.g., winglets	5%	High
• Mid term (5-15 years):		
• Major wing redesign	10%	Medium
• Active flow/separation control	5%	High
• Far term (15+ years):		
• Revolutionary configurations (BWB, oblique wing, hybrid airships)	25%	Medium

Increasing aerodynamic performance of transport and tanker aircraft is possible with changes in geometry that range from minor retrofits to major re-design efforts. Existing aircraft were designed at a time when the relative cost of fuel was far lower than for today's Air Force operations. When increased emphasis is placed on fuel efficiency, the optimal wing design may be quite different. In addition, new technologies may affect the aerodynamic performance and best design.

There is a spectrum of possible wing modifications, ranging from small tip extensions to big winglets with wing structural modification (e.g. those by Aviation Partners) to root plugs (e.g. as in Global Hawk) to entirely new wings. The relatively low cost of such modifications renders this option as “high” in terms of benefit-to-cost. In the mid term, re-winging an aircraft is a more significant development activity than modifying an existing design, but greater gains are possible with changes in platform, airfoil, and/or high lift system that incorporate more advanced technology. Various types of flow control may be used to enhance aerodynamic performance. Simple strakes / vortex generators may control aft body separation on some cargo and transport aircraft, while more advanced active control concepts promise improved maximum lift capabilities that could be translated in some cases to reductions in cruise drag. These technologies provide a large range of potential advantages and costs with simple near term solutions looking very attractive and more ambitious active flow control technologies still very speculative.

Beyond wing re-design is a more complete re-design of the entire aircraft. This is a farther-term solution and again offers the potential for even greater fuel savings. Complete aircraft re-design may be required to fully exploit advances in aerodynamics, materials, flight controls, and engines. Reduced tail size enabled by stability augmentation and revised geometry to efficiently accommodate higher bypass ratio engines are examples of how new technologies

may require more significant changes than re-winging. In addition, entirely new configurations may lead directly to improved fuel efficiency. Concepts such as the blended wing body, oblique wings, or hybrid airships may lead to fuel savings of 25% and more compared with existing designs intended for similar missions. Of course, the cost and risk associated with a major new program to develop an entirely new configuration are high, and detailed studies would be needed to compare the cost effectiveness of this spectrum of potential solutions.



Relatively small near term retrofit modifications to the basic wing structure of air mobility aircraft – specifically by the addition of winglets or planar wing tip extensions – can lead to significant improvements in fuel efficiency. Experience with similar retrofits of commercial aviation aircraft, with wing structures roughly similar to those of many Air Force tanker and transport aircraft, has shown that winglets and wing tip extensions can increase lift-to-drag ratios by 4% – 7% while entailing only relatively small changes to the wing structure.

Both winglets and wing tip extensions operate by increasing the effective wingspan, producing an increase in lift and a reduction in induced drag. Generally, the winglet effect on drag is similar to that produced by wing tip extensions with spans of about half the winglet height. Winglets have the added benefit of not increasing the physical wingspan, and thus can avoid the need for additional ramp space. Under some circumstances, the resulting wing load distributions can also make winglets a more desirable approach.

The benefits of increased lift-to-drag ratio (L/D) produced by either winglets or wing tip extensions can be weighed via the Breguet range equation against the added structural weight of these modifications. When unconstrained by buffet, maximum L/D increases roughly in proportion to the effective wingspan. Under these circumstances there can be a substantial net benefit in fuel efficiency from such near term wing modifications.

In the mid term, winglets or wing tip extensions may provide additional opportunities for further increases in fuel efficiency through synergy between aerodynamic and structures. For example, new materials or active load control could allow for even larger increases in effective wingspan of winglets or wing tip extensions, and thus even greater L/D increases, by extending the limits imposed by buffet or aeroelasticity.

Commercial airlines are currently retrofitting many of their aircraft with winglets to gain fuel efficiency benefits. Most new commercial aviation aircraft being sold today are equipped with winglets, primarily for fuel efficiency reasons. For at least some types of air mobility aircraft, especially those present in relatively large numbers in the Air Force fleet, winglets can provide a substantial improvement in fuel efficiency at a relatively modest cost.

Structures/Materials Solutions: Benefits/Cost

	Δ FE	Δ FE/ Cost
Near term (0-5 years):		
• Integrated vehicle health monitoring	1%	Medium
Mid term (5-15 years):		
• Structural design & optimization, active wing load control	15%	Medium
Far term (15+ years):		
• Advanced design & analysis tools	10%	High

The benefits in terms of incremental fuel efficiency and relative benefits/costs for Structures/Materials Solutions are shown in this chart.

In the near term, Integrated Vehicle (structural) Health Monitoring systems (IVHM), involving, for example, embedded sensors in structures, may be mature enough to have a small impact on fuel efficiency, even though its larger benefits would be in helping to achieve improved mission reliability and lower maintenance costs. If IVHM is used to reduce structural weight, then its benefits could be appreciable, but the certification communities must endorse the approach, and associated costs make this solution "medium" with respect to an estimated benefit-to-cost ratio.

In the mid term and far term, design, analysis, and optimization methods will continue to mature allowing better use of tailored materials and the elimination of design conservatism in future aircraft. These methods span aircraft level multidisciplinary optimization, optimal integration of structures and systems (such as sensors and propulsion), and optimization of material selection and distribution at the detailed level. For example, using a short, structurally integrated inlet/exhaust with active flow control on a 6G, 15,000 lb class UAV could save up to 500-1000 lbs of structural weight. This category applies best to new designs, but could also apply to existing aircraft if significant structural modifications are required.

Example: Structural Optimization

- **Robust Composite Sandwich Structure (ROCSS) utilizes new technologies such as Pi preform joints, Ti core, and Z-pins to achieve:**
  - ***Reduced inspections, repair downtime, and costs***
  - ***30% acquisition and 20% support cost savings***
  - ***36% weight savings over F-22A baseline (demonstrated)***

Source: Lockheed-Martin

By applying advanced technology, a structural weight reduction of about 30% can be achieved, which translates into a 10% to 15% weight reduction of the aircraft empty weight. This example of a Robust Composite Sandwich Structure (ROCSS) shows the application of advanced composites to reduce the weight of the wing structure on tactical aircraft airframes. Similar gains can be achieved on transport aircraft. Because of the extensive change in structural materials and the design approaches required to exploit them, these kinds of gains can only be achieved on new aircraft systems.

Unfortunately, many advanced technology approaches for structural design have been available for a number of years but have been withheld from the development of new aircraft systems due to their perceived risk by the flight certification community. A concerted effort will be needed to determine what kind and how much investment is required in order to satisfy the risk concerns in both the contractor and government communities.

"Operational" Solutions

	Δ FE	Δ FE/ Cost
• **Near term (0-5 years):**		
• Enhance tracking & reporting of AF fuel utilization	3%	High
• Optimize aircraft operations, e.g.,	5%	High
o Engine out taxi, optim. APU usage		
o Optimal route planning, RVSM*		
• Increased use of simulators / Distributed Mission Training	5%	Medium
• **Mid term (5-15 years):**		
• Autonomous formation flight	15%	High

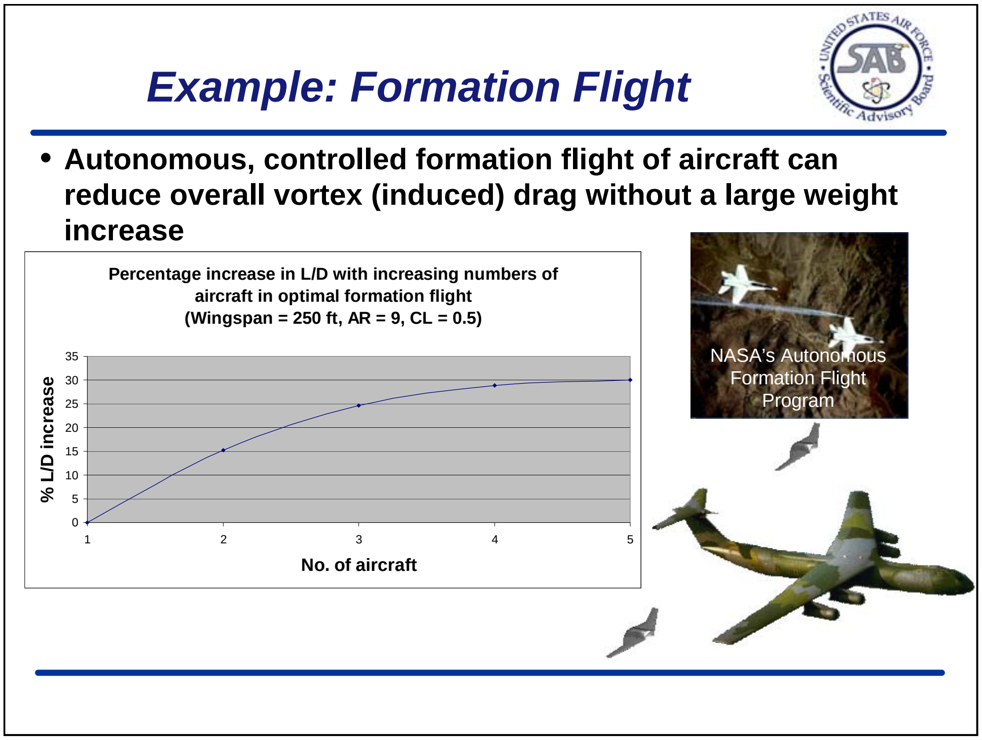
* Reduced Vertical Separation Minimum

The prior sets of charts focused on an evaluation ("findings") pertaining to technological solutions that could impact aircraft fuel efficiency, from the point of view of the engine, the aerodynamics, and the structure. Yet there are also operational issues that could impact aviation fuel utilization. This was not a focus of the current study, but in light of the potential for impact, especially in the near- and mid-term, they were explored to a limited degree. These operational solutions are noted on this chart.

In the near term, the fuel efficiency study members feel that if the Air Force were to expand upon its tracking, reporting, and dissemination of information on fuel utilization (by bases, major commands, etc.), this dissemination could ultimately affect fuel efficiency. If organizations are made aware that reducing their fuel utilization will be positively viewed (and potentially rewarded) by the AF, then greater efforts will likely be made to do so. Increased reporting would be relatively inexpensive to implement but could have a non-negligible, positive impact on fuel efficiency.

Similarly, if practices now routinely done by US airlines are implemented in AF aircraft operations, further reductions in fuel utilization could be possible. These practices include engine-out taxi whenever possible, reduction/optimization of use of the aircraft's auxiliary power unit (APU), optimization of route planning to account for winds and weather (for drag reduction), and reduction of the vertical separation minimum between multiple (transport or other) aircraft flying a similar path. Again, these practices could have a minimal impact on costs but could provide significant fuel economy. Increased use of simulators, particularly in the context of Distributed Mission Training (DMT) utilizing a range of aircraft types, could also positively impact AF fuel efficiency overall, yet with likely more substantial costs than the other solutions noted.

Autonomous formation flight of multiple aircraft is an intriguing concept that could potentially have a significant impact on improved fuel efficiency in the mid term. Details on formation flight are provided on the following chart.



Formation flight of aircraft involves multiple aircraft flying in close proximity to the vortex wakes of adjacent vehicles to effectively increase the span of the system and reduce the overall vortex (induced) drag. Formation flight is used by birds to improve the performance of the flock as a whole; for aircraft, formation flight could be used to increase the effective L/D for the system of vehicles and thus improve the fuel efficiency.

The figure above shows how the L/D of an aspect ratio 9 aircraft at a lift coefficient fixed at 0.5 could be improved by flying in formation with identical aircraft. The overall L/D of the system may be increased by 15% with just two aircraft and 25% with three aircraft. This represents a very large gain that has not been exploited due partly to the difficulty in sustained precision station-keeping. This may be resolved with newly developed autonomous navigation and control systems such as that demonstrated by NASA's autonomous formation flight program in 2001 using two F/A-18s. NASA demonstrated a 14% reduction in fuel consumption for the trailing aircraft, optimally positioned in the wake of the second aircraft. This represents about 50% of the theoretical savings predicted for the system of two transport aircraft, but suggests the potential for increased fuel efficiency even for aircraft not especially well-suited for efficient formation flight.

Further details on the NASA Autonomous Formation Flight program may be found at http://www.nasa.gov/centers/dryden/history/pastprojects/AFF/index.html

The concept may also be applied to formations of long endurance UAVs or heterogeneous groups of aircraft. Recent studies by Lockheed Martin suggest that small UAVs could fly in the wake of a large tanker with all of the power required for UAV flight extracted from the tanker vortex wake near the wing tips (shown notionally in the lower right graphic on this chart).

Alternative Fuels: Benefits/Cost

	Δ FE	Benefit / Cost
• **Near term (0-5 years):**		
• Fischer-Tropsch fuel from coal*	1%	High
• **Mid term (5-15 years):**		
• Oil shale*	1%	Medium
• Other HC: LNG, ethanol blends,* biodiesel*	1%	High
• Hydrogen for fuel cells in APUs	1%	Medium
• **Far term (15+ years):**		
• Biomass: black liquor fuels*	1%	High
• Hydrogen fuel for turbine engines	5%	Medium

* As a means of providing a MORE ASSURED fuel source

While utilizing alternative fuels may not directly impact the "fuel efficiency" of a given vehicle to any significant extent, this fuel efficiency study views the development of alternatives to crude oil-based fuels to be of critical importance to the Air Force, since these fuels can be produced domestically and are therefore a relatively secure supply. Hence the present study did explore, in a limited way, potential alternative fuels that could be used in air vehicles in particular. In this chart, the ΔFE parameter should be viewed to be notional (and in fact may actually be zero or possibly even negative for a given fuel). The "benefit" in the benefit-to-cost ratio here derives from the potentially extraordinary benefits that would be associated with access to a more assured, domestically-generated source of fuel.

The U.S. is rich in hydrocarbon reserves; however, the vast majority of our reserves are in the form of coal or oil shale rather than easily extracted oil. For example, at our current rate of consumption, it is estimated that liquid fuel derived from coal by the Fischer-Tropsch (F-T) process would ensure a 100-year supply of oil. Technologies have been demonstrated in large-scale production in South Africa for the conversion of coal into high-quality fuels that are suitable for aviation. The "off-the-shelf" F-T process appears to be the sole viable short term option. Further information on the F-T process is given in the following chart.

While extraction of oil via pyrolysis from shale and tar sands is done extensively in Canada (from whom the U.S. imports substantial amounts of fuel at present), and while the U.S. does have sizable oil shale reserves (by some estimates, the equivalent of 1 trillion barrels of crude oil), extraction of oil from shale is not without its challenges. Significant environmental degradation, release of toxins, and requirements for sustained economic development, which were not heeded during short term investments in oil shale in the U.S. during the 1970s all present challenges that make this alternative fuel expensive and potentially viable in the mid term, at best.

In addition to mining and processing coal, fuel can be synthesized from plant materials (biomass), which we view as potentially feasible in the near-to-mid term. Ethanol is already blended with gasoline in many states, with about 2% of gasoline sold in 2004 containing some ethanol. Scaling up the current corn-based ethanol production process to yield a significant fraction of the nation's liquid fuel needs is possible, especially for automotive needs; however, the high energy inputs to grow the corn make this approach unattractive from energetic and environmental perspectives. The development of cellulosic (switchgrass)-based ethanol processes appears very favorable and will be discussed in backup charts for this study's report. Yet the somewhat lower energy density of ethanol as compared with aviation fuels makes it less attractive for the present applications, and has potential mainly as a fuel blend.

Biodiesel has also been promoted as an alternative fuel and has seen significant commercial development in Europe. This fuel, which consists of fatty acid alkyl esters, is a cleaner burning diesel replacement made from renewable sources such as new or used vegetable oils and animal fats. Just like petroleum diesel, biodiesel is most suitable for compression-ignition engines. Blends of up to 20% biodiesel mixed with petroleum diesel fuels can be used in nearly all diesel engines and are compatible with most storage and distribution equipment. While biodiesel is not suitable for use as a replacement for conventional jet fuel, it could favorably impact aircraft and air base ground operations.

In the far term, black liquor gasification is a promising alternative for recovery of energy and chemicals from spent pulping liquor (black liquor) in the pulp and paper industry. Because the organic fraction of black liquor comes from biomass, it is a carbon-neutral fuel and is classified as a renewable energy resource. Large-scale adoption of black liquor gasification technology in an integrated gasification combined-cycle (IGCC) configuration would allow production of more than 20,000 megawatts of green electricity in the U.S. alone. As with biodiesel fuels, it is likely that black liquor gasification processes would indirectly impact aircraft efficiencies through ground operations.

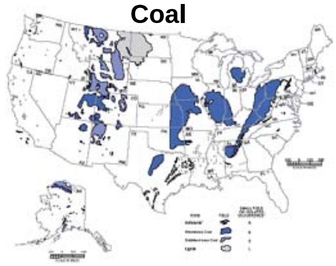
Hydrogen can be used in fuel cells for aircraft auxiliary power units (APUs) in the mid term, or perhaps even sooner if economically viable hydrogen production is achieved. As a fuel for gas turbine or other engines, however, there are significant challenges that make hydrogen less attractive. Although hydrogen has a heat of combustion per mass that is a factor of three higher than that of Jet A, its energy density by volume (as a liquid) is only one-fourth that of Jet A. The large volume needed by cryogenically cooled hydrogen storage tanks moreover will create challenges for airframe designers.

Beyond this, the greenhouse effects associated with producing hydrogen remain a significant concern, since hydrocarbons are the source for 96% of the current hydrogen production, and carbon dioxide is therefore a by-product. Sequestration of CO_2 is clearly required for such processing, hence simply burning hydrogen in an air-breathing (or other) engine will not in and of itself reduce greenhouse gas emissions overall. Hydrogen can be generated by the electrolysis of water, which will not produce greenhouse gases if the electricity is generated by nuclear or renewable sources. Hydrogen production from nuclear fission is also a possibility, but then issues of radioactive waste, generation of plutonium, etc. must be reckoned with. Overall, the fuel efficiency study found hydrogen to be less promising as an alternative fuel and perhaps only viable (from a thermodynamic as well as an economic perspective) in the far term.

The commercial viability of alternative fuels in general will be determined by whether or not there will be a long term high price (>$2.00/gallon) for gasoline refined from crude oil. In Canada, the government provided incentives for the development of oil sands in Alberta, which are now being converted into oil on a large scale. In Brazil, the government mandated the growth of domestic ethanol supplies since the oil embargo of the 1970s. Sugarcane is the primary source of the biomass for ethanol production, which is a crop well-suited to the semi-tropical climate in large areas of Brazil. The result of this three-decade national mandate was the recent declaration by Brazil's president that the country has eliminated all imports of foreign oil. After ignoring the question of assured energy supplies for the past three decades, the U.S. must establish and follow through on a coherent energy policy to reduce our dependence on oil imports from insecure sources in the Middle East and Latin America.

Example: Fischer-Tropsch Synthetic Fuel

- **Synthetic fuel from coal via gasification and FT processing**
  - **~ 900 B barrels of FT fuel from coal in US**
  - **vs. 32 B barrels via enhanced oil recovery**
  - **vs. 685 B barrels of crude oil in Mideast**
  - **By-products: H2, power generation from tail gas, ammonia, naphtha**



- **OSD/DOE studies show significant benefits of FT fuels:**
  - **Superior low temp properties, thermal stability, high heat sink**
  - **Fewer pollutants (reduced CO2, PM, no SOx)**
  - **Elastomer shrinkage and lubricity degradation resolved via blends**

Air Force has ability to catalyze large-scale transition to alternative fuels

Different alternative fuels vary greatly in their properties as well as in the ease with which they can be introduced into the marketplace. As noted, in most cases these fuels do not increase engine efficiency or reduce greenhouse gas emissions significantly, but they do offer the possibility of domestically generated, relatively secure fuel sources. The renewed interested in Fischer-Tropsch (F-T) fuel from coal is due to the maturity of this technology and the relative ease with which existing engines could be adapted to it, as well as its high energy density. During the Apartheid era and ensuing embargo, South Africa developed and still utilizes Fischer-Tropsch processing plants to extract fuel from their vast coal stores, becoming essentially energy independent. F-T fuels do not have a significant greenhouse gas benefit, in contrast to biomass fuels. As a result, F-T fuels may not be the focus of as much U.S. investment development for general transportation uses, in contrast to cellulosic ethanol or biodiesel. Yet as a replacement for aviation fuel, F-T fuels are very attractive, suggesting the potential for significant benefits from government (DoD/AF) technological investment.

The U.S. has about 900 billion barrels of F-T fuel which could be extracted by coal gasification, followed by the F-T process (see more on the process in the backup charts for this report). Montana alone is estimated to have 180 billion barrels of F-T reserves, which could be extracted by strip-mining shallow coal deposits in the eastern portion of the state. The F-T process uses gasified coal or natural gas to form a wax, which is then refined by hydrocracking into a highly paraffinic fuel. The Great Plains Synthetic Fuel Plant near Beulah, North Dakota was built after the 1970s energy crisis and is still in operation, producing 54 billion cubic feet of gas annually using the F-T process at a cost of less than half the current market price.

NASA has studied combustion of liquid fuels made from tar sands and coal. In general, they found that vaporization characteristics of the alternative fuels differed from those of standard fuels and, in the conventional combustors used, flame temperatures were lower than

expected (Rollbuhler, 1989). Fischer-Tropsch fuels have been found to have some advantages when compared with JP-8 jet fuel, such as lower particulates and carbon dioxide emissions, as well as superior low-temperature and thermal properties (W. E. Harrison, OSD/DOE Assured Fuels Initiative). In addition, F-T fuels are said to reduce TSFC by 2.5% and fuel weight by 6%, which are significant improvements. However, due to the significant content of aromatic naphtha in F-T fuels, they have more solvent “power” than conventional fuels. As a result, there have been problems with the degradation of polymer seals in conventional fuel systems when there is a switch to F-T fuel. Degradation in lubricity is also known to be a problem in F-T fuels. Blending has been shown to be a workable solution to the problem of elastomer shrinkage as well as lubricity. Fuel additives have also been shown to improve lubricity in F-T fuels tested in automotive engines. In the long run, new seal materials could be developed which would be resistant to F-T fuel. Finally, the combustion performance of F-T fuel is equivalent to that of RP-1 and RP-2, which makes F-T promising as a single fuel for the AF and DoD.

As noted above, the coal gasification process leads to carbon dioxide emissions, as well as oxides of nitrogen and other pollutants. Sequestration of the carbon dioxide is being explored in some cases, due to the likely imposition of the Kyoto Treaty’s provisions in the future. Depending on the impurity content of the coal, sulfur, and mercury emissions could be significant. The slag from coal gasification is not considered to be hazardous waste and can be disposed of in landfills. In summary, the environmental impact of an F-T plant is similar to that of a modern coal-burning power plant. Nevertheless, as an alternative to aviation fuels or as a fuel blend, F-T fuels hold a great deal of promise in the U.S.

4. Recommendations

Recommendations: Near Term

- Fuel efficiency needs to be a **key performance parameter***
- Expand AF-wide **fuel utilization tracking/reporting**
- Pursue **near term solutions**:
  - Engine fan wash
  - Aircraft operations: engine-out taxi, optimal route planning, RVSM
  - Winglets, wing extensions
- Ramp up development and utilization of **F-T fuels**
  - Continue assessment via Assured Fuels Init., AFRL/PR
  - AF should take the **lead** in DOD's transition to new fuels via fuel blends

*Rec. from DSB 2001 task force

Based on the aforementioned findings and comparison among alternative technological, operational, and alternative fuel solutions, the fuel efficiency study recommends that the Air Force take the following actions in the near term:

- Establish fuel efficiency as a key performance parameter (KPP) for the design, development, and acquisition phases of new aircraft. Fuel efficiency should become an integral part of the evaluations of Air Force bases and commands.
- Expand fuel utilization, tracking, and dissemination to an Air Force wide activity. This is also critical in determining the effect of aircraft fuel efficiency on saving dollars in terms of operations, infrastructure, etc.
- Pursue relatively simple near term solutions for reduction of fuel consumption: engine fan wash, improved aircraft operations (engine-out taxi, optimal route planning, reduced vertical separation minimum [RVSM], etc.), and winglets and wing extensions. These technologies are all mature, have quantifiable cost/benefit analyses, and can be implemented or purchased in the short term.
- Ramp up the exploration, development, and utilization of Fischer-Tropsch (F-T) fuels for aviation applications. This technology will allow the U.S. to become more independent of foreign sources of fuel over time. The Air Force should take the lead in transitioning the DoD to new fuels via F-T fuel blends with current aviation fuels. A government initiative in F-T fuels would provide incentives for commercial uses of

such fuels and would provide an accelerated technology development path, tapping into the United States' substantial coal reserves.

Recommendations: Mid & Far Term

- **Pursue technical solutions today for the mid and far term:**
  - **Propulsion technologies**
    - **e.g., adaptive, ultra-efficient engines via sensors, controls, and advanced materials**
    - **e.g., explore re-engining, accounting for "fully burdened" fuel cost**
  - **Aerodynamic technologies**
    - **e.g., revolutionary wing/aircraft designs**
  - **Structures/materials technologies**
    - **e.g., integrated vehicle structural optimization and design**
  - **Aircraft operations**
    - **e.g., autonomous formation flight**
  - **Alternative fuels**
    - **e.g., ethanol, alternative HC fuel blends**

Based on the aforementioned findings and comparisons among solutions, the study recommends that the Air Force take the following actions in the mid and far term:

With respect to propulsion and engine technologies, significant improvements in fuel efficiency, on the order of 15 - 20%, can be achieved by pursuing "intelligent" or adaptive gas-turbine engine technologies. Improved materials to allow higher combustion temperatures and higher compression ratios will allow the engine to achieve higher efficiency. Air Force transports and tankers are required to operate over a wider range of conditions than do civilian transports, which implies that adaptive-engine control technologies will be especially important to achieve overall improvements in fuel efficiency.

There are a wide range of technologies that can contribute to achieving airbreathing engine adaptability and control, including, for example, laser-diode remote combustion sensors, SiC intermediate-temperature electronics and sensors, sensors and processes for active tip clearance control, actively controlled turbine blade cooling, and inlet flow sensing and control. Such technologies require long term, sustained funding to validate the concepts, materials, manufacturing, and reliability. However, the funding structure for gas-turbine research in the US has become inconsistent in recent years; even programs such as VAATE have had funding instabilities.

It is the opinion of this study that the Air Force and DoD should revisit the economics of re-engining the existing tankers and transports, but in this case, using the "fully burdened" cost of fuel in the analysis. The economic case for re-engining will change dramatically if even a fraction of the tanker-delivered fuel cost is used in the calculation.

Advances in aerodynamic technologies and airframe design are likely to make a positive impact on effective fuel efficiency over the mid- to far-term. For example, rather revolutionary

configurations such as the blended wing body could constitute a more fuel efficient design for future tankers and transports. Advanced, lightweight materials and integrated vehicle structural optimization could similarly produce benefits for efficiency. On the operations side, autonomous formation flight has been shown to provide surprisingly large improvements in overall fuel efficiency due to overall reduced drag. In this case, the technical challenge is to develop and test the control system and associated software needed for collaborative, autonomous flight.

Finally, as noted previously, recent worldwide events and associated oil price instabilities have revived interest in and the critical need for alternative fuels. While Fischer-Tropsch fuels appear to hold the greatest promise as a near term replacement for aviation fuels, other hydrocarbon fuels may too play a role. While it is more likely to play a major role in the coming decade as an automotive fuel, ethanol as well as other alternative hydrocarbons could be used as blends for both ground vehicles and air vehicles.

One Final Thought ...

"The fast-changing world energy situation could significantly influence the nature of future international conflicts and the effectiveness with which the United States Air Force could execute its missions. The 'energy issue' has assumed a prominent position in both short- and long-term Air Force planning.

"Uncertainties in the future availability and economics of crude-oil-based jet fuels pose a particular challenge to the Air Force, the largest DOD consumer of jet fuel. To meet this challenge the Air Force will be obliged to undertake measures to conserve jet fuel in the short term and to develop a future capability for using jet fuels derived from alternatives to crude oil."

RAND Corp. Report R-1829-PR, December, 1976

As a closing comment, the fuel efficiency study came across a quote (in fact, taken from the introduction to a RAND report written in 1976) that captures many of the sentiments that members feel regarding the current situation that the U.S. and the Air Force find itself in with respect to fuel and energy efficiency. Today, as in 1976, there are increasing gaps between U.S. fuel consumption and crude oil production. Significant increases in the price of crude oil have made the widespread availability of fuel to carry out military missions more difficult. The study views the issue of fuel efficiency as one that can significantly impact future military capabilities, requiring an immediate, well-planned investment strategy for the development of improved air vehicles and provision of an array of alternative fuels for the nation.

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Appendix A: Terms of Reference

USAF Scientific Advisory Board

Quick Look Study

FY 2006

Technology Options for Improved Air Vehicle Fuel Efficiency

Terms of Reference

Background
Recent increases in aircraft fuel costs, as well as volatility in the worldwide fossil fuel market, can have a negatively impacts on U.S. Air Force capabilities and missions. Over 80% of the total USAF energy consumption, for example, is associated with aviation fuel. For a number of years, the Air Force Research Laboratory, in partnership with industry and other government entities, has pursued advanced research and development programs which in part have sought to improve aircraft engine efficiency and reduce vehicle drag. In light of the need for reductions in fuel costs and the operational need for long range and persistence, it is of interest to determine technological solutions for improvements in fuel efficiency for today's Air Force fleet and for future air vehicles. Our Air Force mission requires range and persistence in our aircraft. To do this we must reduce our fuel costs and explore technological solutions to increase fuel efficiency.

Study Products
Briefing to SAF/OS & AF/CC in January 2006. Publish report in March 2006.

Charter
The "quick look" study will explore potential improvements in fuel efficiency by providing the following:

- An overview of the relevant trades among air vehicle efficiency, performance, emissions, and noise.
- A brief assessment of the accomplishments and potential future benefits of recent AFRL, industry, and other government programs relevant to improved fuel efficiency and reduced aircraft fuel costs. Examples could include the Integrated High Performance Turbine Engine Technology (IHPTET) program, the Versatile Affordable Advanced Turbine Engines (VAATE) program, and various vehicle management and advanced materials programs.
- An assessment of potential technologies that could be used for reducing fuel consumption and lifecycle costs by the current Air Force fleet.
- An assessment of potential technologies that could be used for improved fuel consumption by air vehicles, especially in the near term, but in the mid term and far term as well. Near and mid term technologies may include and emphasize retrofit and/or alternative fuels, while far term technologies may require new R&D for yet-to-be-defined propulsion/air vehicle systems.
- Provide topics for follow-on studies in support of an Air Force Energy Strategy.

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Appendix B: Study Members

Study Chair

Prof. Ann Karagozian*	University of California, Los Angeles Dept. of Mechanical and Aerospace Engineering

Study Members

Prof. Werner Dahm*	University of Michigan Dept. of Aerospace Engineering
Mr. Ed Glasgow*	Lockheed-Martin Aeronautics Company Advanced Development Programs
Prof. Roger Howe*	Stanford University Dept. of Electrical Engineering
Prof. Ilan Kroo*	Stanford University Dept. of Aeronautics and Astronautics also with Desktop Aeronautics, Inc.
Prof. Richard Murray*	California Institute of Technology Control and Dynamical Systems
Ms. Heidi Shyu (ex officio)*	Raytheon Company Space and Airborne Systems

Study Management and Support

Lt Col Ki Ho Kang, USAFR AF/SB – Executive Officer

Maj Mike Walker, USAFR AF/SB – Executive Officer

Mr. Justin Waters, AF/SB – Analyst

Capt Candice Pipes, USAFA – Technical Writer

*Denotes current status as a member of the Air Force Scientific Advisory Board.

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Appendix C: Visits and Briefings

Air Force

Assistant Secretary of the Air Force (Financial Management & Comptroller)
Deputy Chief of Staff of the Air Force (Logistics, Installations & Mission Support)
Air Mobility Command
Air Force Research Laboratory
- Propulsion Directorate
- Air Vehicles Directorate
- Air Force Office of Scientific Research
  - European Office of Aerospace Research & Development

Other Government / FFRDCs

OSD/DOE Assured Fuels Initiative
NASA
Federal Aviation Administration
Rand Corporation
Sandia National Laboratories

Industry

Aviation Partners
Boeing
British Petroleum (BP)
General Electric
Honeywell
International Air Transport Association
Lockheed Martin
Northrop Grumman
Pratt & Whitney
Rolls-Royce

Universities

Massachusetts Institute of Technology

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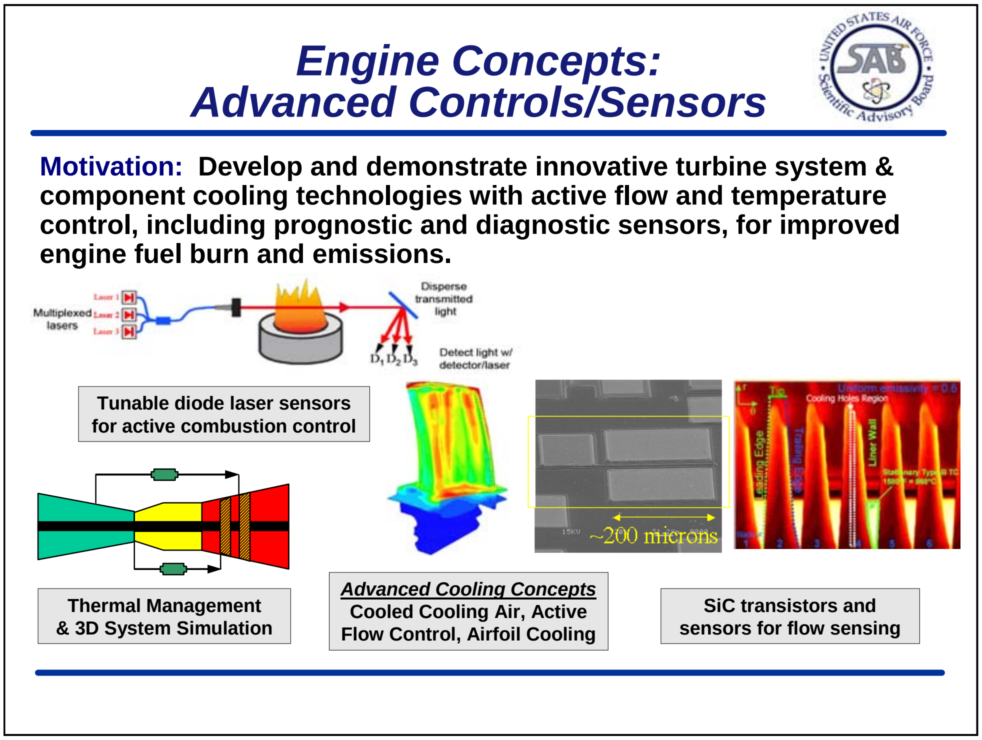
Appendix D: Acronyms and Abbreviations

ADVENT	Adaptive Versatile Engine Technologies
AF	Air Force
AFRL	Air Force Research Laboratory
AFRL/PR	Air Force Research Laboratory, Propulsion Directorate
APU	Auxiliary Power Unit
B	Billion
BPR	Bypass ratio
BWB	Blended Wing Body
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CONUS	Continental United States
DESC	Defense Energy Support Center
DMT	Distributed Mission Training
DoD	Department of Defense
DOE	Department of Energy
DSB	Defense Science Board
FE	Fuel Efficiency metric
F-T	Fischer-Tropsch
FY	Fiscal Year
H_2	Molecular hydrogen
HC	Hydrocarbon
IATA	International Air Transport Association
IGCC	Integrated gasification combined-cycle
IHPTET	Integrated High Performance Turbine Engine Technology
IVHM	Integrated Vehicle Health Monitoring
JSF	Joint Strike Fighter
KPP	Key performance parameter
L/D	Lift-to-drag ratio
LNG	Liquefied Natural Gas
LO	Low observable

NO_x	Nitrogen Oxides
OEW	Operating Empty Weight
OPR	Overall pressure ratio
OSD	Office of the Secretary of Defense
PDEs	Pulse Detonation Engines
PM	Particulate matter
R&D	Research and development
ROCSS	Robust Composite Sandwich Structure
RVSM	Reduced Vertical Separation Minimum
SAB	Scientific Advisory Board
SiC	Silicon carbide
SO_2	Sulfur dioxide
SO_x	Sulfur oxides
SPM	Smart Product Modeling
T/W	Thrust-to-weight ratio
T3	Combustor inlet temperature
T4	Turbine inlet temperature
TIT	Turbine inlet temperature
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Aerial Vehicle
UEET	Ultra Efficient Engine Technology
UHB	Ultra-high bypass
USAF	United States Air Force
UTRC	United Technologies Research Center
VAATE	Versatile Affordable Advanced Turbine Engine
W_{fuel}	Fuel weight
W_O	Vehicle dry weight
W_{PL}	Payload weight
η_o	Overall engine efficiency

Appendix E: Elaboration on Additional Promising Technologies



The largest gains in specific fuel consumption were achieved by the introduction of low bypass turbofans in the 1950s followed by high bypass turbofans in the 1980s. However, there remain significant improvements in fuel efficiency, on the order of 15 - 20% beyond the present state-of-the-art, that can be achieved through improved closed-loop control on all aspects of the engine, as well as improved materials. The opportunities for improvement in TSFC through the introduction of advanced technology in the various subsystems have been estimated in the recently ended NASA-led UEET program. The changes are generally less than 10% for a specific technology and the effects of multiple technologies may not be additive. To the extent that closed-loop control leads to greater adaptability, advanced engine technologies may play a more important role in enhancing fuel economy for the more varied missions of Air Force transports and tankers than for civilian aviation.

Combustion processes could be improved through the introduction of tunable diode lasers to monitor remotely the reaction products. These devices have been shown to provide reliable measurements of fuel/air ratio in stationary gas turbines. The high-vibration environment experienced by aircraft engines will require improvements in the robustness of the fiber-optic interconnects to the diode lasers. By improving the measurement bandwidth of these sensors, it may be possible to take advantage of new, more efficient combustion schemes. The intermediate temperatures in a gas turbine (500-600^{o}C) are too hot for conventional silicon sensors and electronics. NASA Glenn researchers have pioneered silicon carbide integrated-circuit and micromachining technologies to make these areas accessible for sensing pressure and shear.

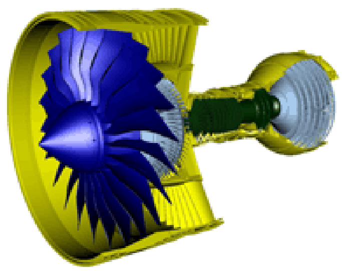
In order to affect flow or combustion processes in the gas turbine, low-power, high-bandwidth actuators are needed that can operate reliably in extreme environments. For example, active tip-clearance control could have a significant impact on fuel efficiency, but the actuators are still under development. In the case of actuators for inlet flow-control, added cost, weight, and reliability are issues.

Due to the small size of the gas turbine sensor and actuator markets, they do not justify large investments to create technologies that meet their demanding requirements. In the past, vertically integrated manufacturers might invest in subsystem technologies if their impact on overall performance was sufficiently high. Today, the sensor, actuator, and control-system subcontractors must make independent economic cases for investment in new technologies.

Engine Concepts: Advanced High BPR Engines

In mid-term (5-15 years), high bypass ratio gas turbine engines can provide substantially higher fuel efficiency for air mobility aircraft

High BPR Turbofan



Ultra-high BPR Propfan

5-10 years: Advanced turbofan engines with further increased BPR
10-15 years: Unducted propfan engines based on 1980's NASA work

In the mid term, over the next 5-15 years, the continued development of high bypass ratio (BPR) gas turbine engines can be expected to lead to further improvements in fuel efficiency for air mobility aircraft.

Engines appearing 5-10 years from now will be evolutionary, based on current ducted turbofan approaches but with bypass ratios exceeding 10:1. These will include three-spool designs, hollow fan blades, highly-swept blade shapes, and other derivatives of current technologies. Many of these evolutionary design improvements rely on the VAATE program.

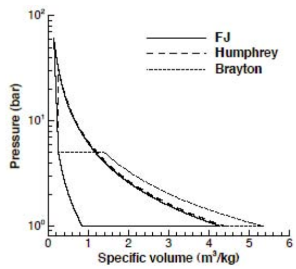
Farther into the mid term, engines appearing 10-15 years from now will include more radical departures from present designs. Some will involve ultra-high bypass (UHB) engines based on the propfan approach. Propfans are unducted turbofan engines that obtain the high propulsive efficiency of a turboprop, but use highly-swept blade shapes and contra-rotating fan pairs to allow the high rotation rates needed for transonic flight.

Propfan technologies were developed and demonstrated in the 1970's and 1980's. Successful flight demonstrations of Pratt & Whitney (578-DX) and GE (GE-36) propfan engines showed 30% improvement in fuel efficiency over conventional turbofan engines. Russia has flown an Antonov AN-70 with four contra-rotating propfan engines. Although these research results were promising, the drop in oil prices of the early 1980's led to weak interest from the airlines, and further development was largely ended. The recent rise in oil prices will likely renew work on propfan engines.

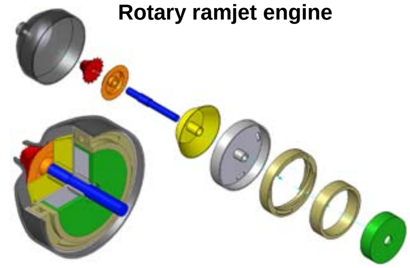
Engine Concepts: Revolutionary Engines

In the far-term (>15 years), revolutionary engines may be based on detonation cycles, wave rotors, and rotary ramjets

Pulsed detonation engine



Rotary ramjet engine



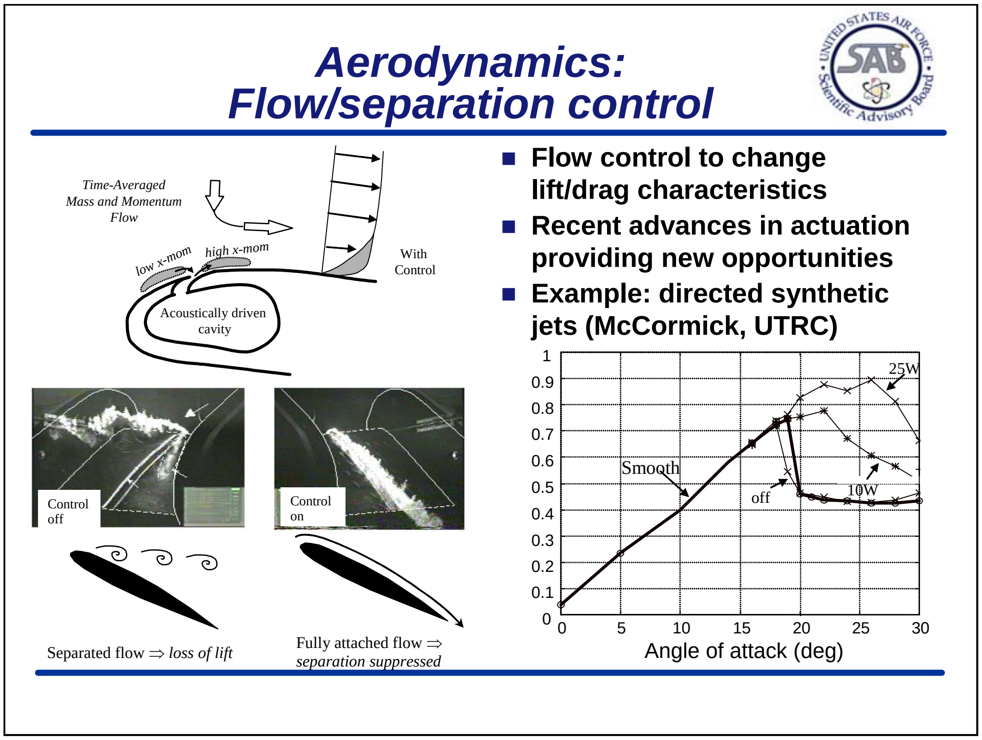
- **Detonation engines based on Humphrey cycle can achieve higher efficiency than gas turbines based on Brayton cycle**
- **Rotary ramjets have efficiency and weight benefits of conventional ramjets but can operate at all flight speeds**

In the far term, engines appearing 15-25 years from now will include revolutionary designs that bear little resemblance to current gas turbine engines. These offer fuel efficiencies that are significantly higher than current engine approaches.

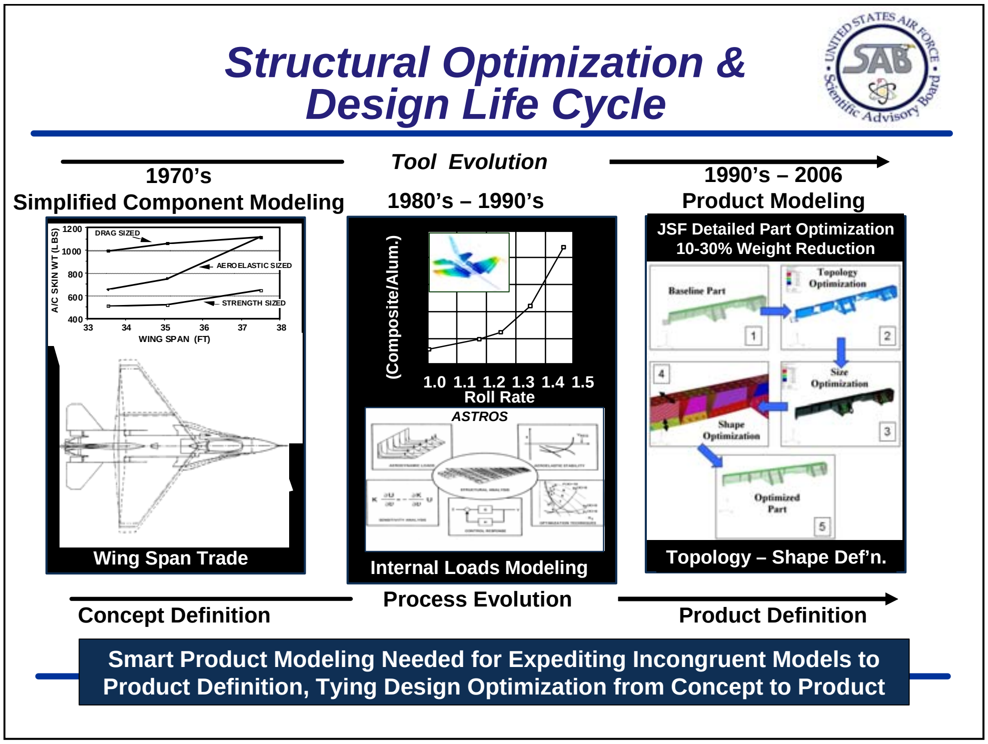
Some of these will be detonation engines, including pulsed detonation engines (PDE's), detonation turbojets ("turbodets"), and detonation ramjets ("dramjets"). All of these operate on the Humphrey cycle, in which constant-volume detonation replaces the constant-pressure combustion of the Brayton cycle on which gas turbines operate. The constant-volume detonation leads to a higher fuel efficiency for the thermodynamic cycle. Wave rotors, which have been researched for decades, may find a useful role in such engines.

Other approaches may be based on rotary ramjets, but these will differ fundamentally from earlier embodiments as rotary-wing propulsion systems. Recent work to develop such systems replaces the conventional compressor and turbine in traditional gas turbine engines with a single supersonic circumferential rotor, having integrated shaped ceramic varying-area ramjet channels that provide near-isentropic gasdynamic compression and expansion in a high-efficiency engine. The resulting systems can achieve higher power density, increased efficiency, increased durability, and reduced cost over conventional gas turbine engines.

At present, all of these systems are in early stages of the R&D process, and technology risks associated with them are substantial. At most one or two such approaches will mature in the far term to replace current gas turbine engines; however, they offer the highest potential for dramatic long term increases in fuel efficiency for aircraft engines.



Another promising long term technology for increased performance is aerodynamic flow and separation control. Examples of emerging techniques include the use of "synthetic jets" for keeping flow attached to a wing and the use of combinations of blowing and suction to tailor the flow around leading edges and stagnation points. To date, the main limitation in these techniques is the weight and complexity of the actuation systems, but advances in materials and in wireless technologies could have a favorable impact.



Formal structural optimization methods were conceived in the 1970's and have been continuously matured and applied to problems of increasing complexity. Early aeroelastic synthesis tools have progressed from component applications such as wing span trade studies to more complex applications involving large finite element models. The methods now provide for rapid internal loads models and optimal sizing and can be used to evaluate tradeoffs in materials and design criteria while meeting geometric and other constraints. These methods have enabled improved capability to generate loads for sizing structural parts in the detailed design phase.

Structural and topology optimization methods have now been combined in commercially available software such as OptiStruc. Such methods are being used in the detailed sizing of parts and have resulted in a 10-30% weight reduction over traditional methods.

While tools have been developed and used in the design and optimization, the design process of major programs has changed very little. The full benefits of the design optimization process will only be realized when the high resolution information enabled by Smart Product Modeling (SPM) is used to link the aircraft-level design optimization information with the detailed design process, allowing integrated decision making and configuration management.

Alternative Fuels Comparison

Fuel	Heating Value	Mass Density	Energy Density
JP-8	43 kJ/g	0.81 g/cm^3	34.8 kJ/cm^3
Jet-A	43 kJ/g	0.81 g/cm^3	34.8 kJ/cm^3
Liq. H2	121 kJ/g	0.07 g/cm^3	8.6 kJ/cm^3
Liq. CH4	50 kJ/g	0.42 g/cm^3	21.2 kJ/cm^3
Ethanol	27 kJ/g	0.79 g/cm^3	21.3 kJ/cm^3
Biodiesel	37 kJ/g	0.87 g/cm^3	32.2 kJ/cm^3
F-T Fuel	44 kJ/g	0.76 g/cm^3	33.4 kJ/cm^3

Fischer-Tropsch (F-T) fuel from coal is the most viable alternative for displacing imported oil used in current aviation fuels

For various alternative fuels, this chart compares the fuel heating value and energy density – two key factors that determine the potential suitability of an alternative fuel – with traditional aviation kerosene fuels such JP-8 and Jet-A.

Liquid hydrogen stands out by its exceptionally high heating value, roughly a factor of three above that of most other fuels. However, its mass density is more than an order of magnitude lower than most fuels, and thus its low energy density (kJ/cm^3) would require four times the volume of fuel for the same mission relative to current aviation fuels. Liquid hydrogen is also a hard cryogen, further complicating its use as an aircraft fuel.

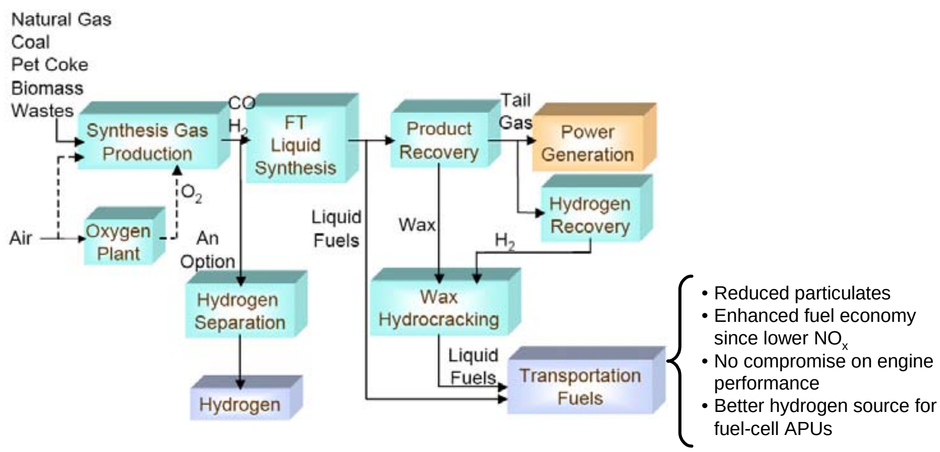
Methane can be liquified at normal temperature, but the required high pressure would necessitate massive fuel tanks. By contrast, ethanol is a liquid at normal temperature and pressure, and thus is used in automotive fuel blends such as E85, but provides only two-thirds the energy density of current aviation fuels. Biodiesel has about the same energy density as aviation fuels, but its lower heating value would require about 15% more fuel mass to be carried for the same mission.

Fischer-Tropsch (F-T) fuel synthesized from coal or oil shale is also liquid at normal temperature and pressure. However unlike ethanol or biodiesel, F-T fuel has nearly the same heating value and energy density as aviation fuels, and thus can be easily blended with these to displace fuel generated from imported oil. F-T fuel is the most promising alternative fuel for achieving greater fuel independence and fuel price stability, as has been described in earlier charts.

One can clearly identify the problem with H_2: significantly lower density, despite a heating value that is four times higher than most jet fuels. Hence storage in the condensed phase is a major issue with hydrogen. One needs a much larger storage tank which is cryogenic on an

aircraft to make this viable; hence the aircraft itself is larger (see a subsequent slide on this issue of aircraft size).

Alt. Fuels: Fischer-Tropsch Fuels



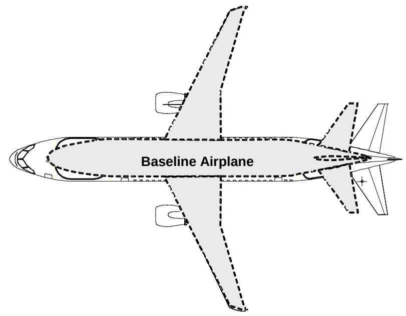
Preliminary Fischer-Tropsch fuels testing at AFRL show improved emissions with no compromise in gas-turbine engine performance

For reference, this chart shows the relevant chemical processes associated with the production of Fischer-Tropsch liquid fuels from coal. Beyond fuel generation for aviation fuels, there are further benefits to F-T fuel utilization. Fischer-Tropsch plants can be operated to generate net electricity (beyond the requirements of the synthesis process) by using part of the gas for power generation. For example, the proposed F-T plant near Scranton, Pennsylvania would be operated to export about 1/3 of the electrical energy generated to the grid. This fact makes it possible to consider an F-T plant as a power plant, which would ease the regulatory and licensing burden. At the same time, the F-T process can be a source of hydrogen and ammonia and naptha, which improves the economics of the process.

Hydrogen as Alternative Fuel

Pros

- **Higher heating value (3X Jet A)**
- **Low density (1/4 Jet A in liquid phase)**
- **Potentially lighter, smaller propulsion systems with structural cooling**
- **No emissions of CO_2, CO, SO_2**
- **Can be generated from non-fossil fuels**



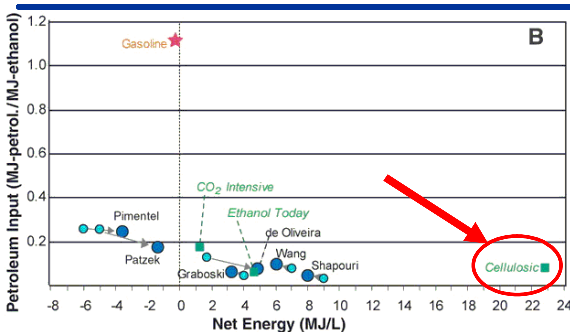
Cons

- **Low energy density (<9 kJ/cm³ vs 35 kJ/cm³ for JP-8)**
- **Wide flammability range (easy ignition)**
- **High pressure cryogenic tanks**
- **Larger aircraft $\Rightarrow$ less efficient**

As noted earlier, it is widely reported that hydrogen has several advantages over current hydrocarbon fuels. It is true that hydrogen has a higher heating value and lower density than Jet-A, and as is widely stated, hydrogen produces no greenhouse gases (e.g., CO_2) during its combustion with air or oxygen. Widespread production of hydrogen poses a significant and non-trivial problem, however. Generation of CO_2 takes place during reforming or other processing of hydrocarbon fuel to create H_2 fuel, thus requiring sequestration. Hydrogen could be generated from non-fossil fuels, e.g., nuclear fission, although this process has its own set of technological challenges, not least of which is the generation of radioactive waste.

Despite these challenges, a number of groups have examined the potential for hydrogen fuel usage in aircraft. There are challenges with respect to energy density since, unfortunately, hydrogen requires over four times the volume for an equivalent amount of energy as contained in Jet A. This translates into the requirement for a larger aircraft for a given range, and hence increased aerodynamic drag. A preliminary study by Boeing and NASA Glenn [**Ref**: Daggett, D., Hadaller, O., Hendricks, R., and Walther, R., "Alternative Fuels and their Potential Impact on Aviation," **ICAS 2006-5.8.2,** 2006] indicates that a 300 nautical mile mission would require 28% more energy utilization with a hydrogen-fueled plane as compared with a conventional plane burning a hydrocarbon-based aviation fuel. The hydrogen plane moreover would be appreciably larger, as shown in this slide.

Ethanol as an Alternative Fuel: Attractive … but not for Aviation



- **Cellulosic ethanol can reduce both petroleum consumption *and* greenhouse gas emissions, according to a recent thorough study***
- **Key element in President's Biorefinery Initiative (State of the Union, 31 Jan. 2006)**

* Graphic from A. E. Farrell, et al, "Ethanol can contribute to energy and environmental goals," Science, 311: 506-508 (2006). Reprinted with permission from AAAS.

Fuel	**-?H°$_{Combustion}$ (kJ/g)**
Jet-A (JP-4) (~$C_{12}H_{26}$)	42.8
Ethanol (C_2H_5OH)	26.8

Low energy density vs. Jet-A means ethanol isn't going to be a viable aviation fuel

As noted previously, ethanol is already blended with gasoline in many states. Scaling up the current corn-based ethanol production process to yield a significant fraction of the nation's liquid fuel needs is possible. Yet the high energy inputs to grow the corn, and the somewhat lower energy density of ethanol, make this approach unattractive for aviation fuels from an energetic perspective. The development of cellulosic (switchgrass)-based ethanol processes appears very favorable, however, as indicated in this slide, showing a significant increase in net energy extracted. Details of the process are discussed in a recent technical publication [A. E. Farrell, et al, "Ethanol can contribute to energy and environmental goals," *Science*, 311: 506-508 (2006)]. Nevertheless, ethanol has relevance for aviation fuels only (at most) in terms of a blend, if it is widely available commercially in the mid term.

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Appendix F: Initial Distribution

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Other Air Force Elements
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    - European Office of Aerospace Research & Development

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OSD/DOE Assured Fuels Initiative

U.S. Navy

Deputy Assistant Secretary of the Navy for Research, Development, Test and Evaluation
Head, Energy Plans, Policy and Technology Branch, Office of the Chief of Naval Operations

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Lockheed Martin

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Rolls-Royce

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14. ABSTRACT
As crude oil prices and worldwide competition for fuel continue to increase, there are added pressures on the United States to simultaneously conserve fuel as well as seek new sources of energy for power generation and transportation systems. Within the U.S. military, increasing costs of fuel directly affect the ability to carry out military missions. Hence it is imperative that the Department of Defense, and the Air Force in particular (as the largest consumer of fuel within the DoD), explore ways in which improved fuel efficiency as well as alternative sources of fuel may be realized.

The Air Force Scientific Advisory Board was thus tasked by the Air Force leadership to perform a "quick look" study exploring potential scientific and technological solutions that could impact energy and fuel efficiency. This report, consisting of an executive summary and annotated briefing with an elaboration of additional promising technologies (Appendix E), is intended to provide a complete discussion on the background, issues, findings, and recommendations from the study, which focused primarily on air vehicles.

15. SUBJECT TERMS
Air Force Scientific Advisory Board, Scientific Advisory Board, SAB, Fuel Efficiency, Fuel Consumption, Fuel Conservation, IHPTET, VAATE, Alternative Energy, Fischer-Tropsch, Synthetic Fuels, Re-engining, Biodiesel, Ethanol, Hydrogen

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